PHOSPHORUS AVAILABILITY IN ALLUVIAL RAINFOREST SOILS FROM COSTA RICA AS AFFECTED BY PHOSPHORUS FERTILIZATION AND SOIL AMENDMENTS

By

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INTRODUCTION

It is an irony that tropical regions of the world, which are considered suited for agriculture during the whole year, are often chronically short in food supply. The low level of agricultural production in these areas has been slow to rise and in some cases, the level of productivity has actually declined. This poor economic situation is aggravated by the fact that population growth has increased at a tremendous rate. The vast agricultural potentials of the tropics must, therefore, be judiciously exploited and fully developed to meet existing needs, improve the nutrition of the people, and avert an impending food crisis.

Our information and understanding about soil fertility problems in the tropics are rather limited as compared with the large body of knowledge that most temperate countries have accumulated through extensive research. Unfortunately farming techniques of the more advanced and developed countries cannot always be directly adapted to developing countries. The same scientific principles, however, can be put to use to develop innovations that will be suitable to local conditions.

The economy of Costa Rica is predominantly agricultural such that about 50% of its gross national product is derived from agriculture (7). The two main export crops are bananas (*Musa sapientum*) and coffee (*Coffea* sp.). The principal crops for the domestic economy are livestock, sugarcane (*Saccharum officinarum* L.) abaca (*Musa textiles*

Hem), cacao (Theobroma cacao L.) and cereal crops. As in most tropical regions, crop yields are well below optimum levels.

In December, 1954, the University of Florida entered into a contract with Servicio Tecnico Interamericano de Cooperacion Agricola (STICA) and the Ministry of Agriculture and Industries (MAI) of Costa Rica to help speed up the agricultural development of the country through the introduction and improvement of programs and training of agricultural technicians. The contract, which ended in June, 1960, resulted in the publication of several papers regarding the agricultural potentials of Costa Rica (7, 22, 148).

There are at least three recognized groups of soils in Costa Rica: latosols, volcanic, and alluvial (22, 182). Workers in the MAI and STICA recognized the existence of N, Mg, Mn, Zn, and B deficiencies in coffee and developed methods for correcting these deficiencies (182). Although some effort has been made to establish soil lime requirements, further studies relating to an adequate liming program would be of benefit. Wander (182) reported that in some areas of Costa Rica, liming the soil resulted in considerable increase in plant growth and disappearance of deficiency symptoms not specifically related to Ca.

Kretschmer (104) found that in about half of the Costa Rican soils tested, three crops responded extremely well to additions of P up to 98 kg/ha. That the crops failed to respond even to the highest rate in other soils, indicated that either insufficient P was supplied or that some other elements were limiting. No obvious relationship existed between general soil type or origin and plant growth, but there appeared to be some positive relationship between level of soil Ca, percentage of Al and Fe oxides, and plant growth.

The case of lime as a limiting factor in plant growth response to applied P in the soil was demonstrated by Kretschmer (104) in a pot experiment with a latosol from San Vito, Costa Rica. In the limed soil, there was a marked plant growth response at 225 kg/ha of applied P and this growth response continued through 1,300 kg/ha. In the unlimed soil, growth was noticeable only where 1,650 kg/ha of P were applied.

Blue (24) initiated N-P-K fertilizer experiments with forages in three major physiographic regions of Costa Rica during the latter part of 1958. At Los Diamantes, he encountered difficulty in establishing grasses on newly cleared land. Later experiments indicated that the problem was not caused by deficiencies of N, K, S, lime, and micronutrients but rather low P availability. Where P was banded by grass rows to give a concentration of approximately 516 kg/ha in the band, pangolagrass (*Digitaria decumbens* Stent) and elephantgrass (*Pennisetum purpureum* Schumach) developed much more rapidly than where P was omitted. Although P was applied broadcast in the earlier experiments, the rates (0 to 172 kg P/ha) were relatively low compared to the concentration in the band. Large quantities of P were extracted from the soil by $0.5\ \underline{N}\ H_2SO_4$ (93 ppm) but this P apparently had limited availability to plants.

Since the Los Diamantes soils have large amounts of P, the knowledge of how to render this P available to plants is of utmost importance, especially as fertilizers are costly. This study was, therefore, conducted with the following objectives:

(a) to determine the amounts of various soil P fractions and how these fractions are affected by liming, cropping, and P fertilization.

(b) to determine the level of applied P which will give optimum forage plant growth.

(c) to obtain information regarding the effects of lime and other soil amendments on soil P availability.

(d) to determine whether other nutritional factors will be affected by lime and should lime impair plant growth, to find appropriate treatment(s) to overcome this adverse effect.

REVIEW OF LITERATURE

The Role of Al and Fe in P Fixation

According to Wild (190), the retention of P by soils was first demonstrated by Way in 1850, although Liebig had anticipated the results at an earlier date. Way found that concentrations of NO_3^-, Cl^-, and $SO_4^=$ in solutions remained unchanged when passed through the soil while phosphates were reduced.

At the beginning of this century, intensive study was started regarding the reactions involved between soil and phosphate ions, especially the role of Al, Fe, and Ca. The idea that Al and Fe were involved, however, was not new. Wild (190) reported that in 1863 Voelcker showed that soil containing a small amount of $CaCO_3$ was active in P retention. Voelcker concluded that this was due to the formation of insoluble compounds with Al hydroxide.

In general, available P is less than 1% of the total soil P at any given time. It is now generally recognized that P recovery by plants immediately after fertilizer application is about 10 to 30%. The remainder which becomes available over long periods of time is precipitated by soluble cations, immobilized by soil micro-organisms, or retained by the soil complex. Phosphate fixation is the conversion of soluble P to a less soluble form, thus reducing its movement in the soil and availability to plants.

Heck (94) and Trung and Ford (178) reported that yellow soils fixed more P than red soils suggesting that fixation by Fe was due largely to the hydrated oxides. Hack (84) considered most of the P applied to latosols to be in the form of basic Fe-P similar to dufrenite ($Fe(OH)_3PO_4$). Ford (64) found that P fixed by limonite was mostly insoluble in 0.003 $\underline{N}$ H_2SO_4. Hematite did not show noticeable P fixing capacity. Dehydration of limonite by heating destroyed its P fixing capacity. In contrast, Ford (64) found that the P fixed by bauxite was of intermediate solubility. Partial dehydration of bauxite increased its fixing capacity. With further dehydration, the fixing capacity was reduced but not eliminated. Latosols of Hawaii were reported by Youngs and Plucknett (194) to fix 25 to 80% of the P contained in a 10,000 ppm P solution after 24 hours of shaking. The hydrated Fe complex accounted for 50 to 65% of the total P fixed by the soils.

Metzger (133) observed that when Fe was removed from the soil, its capacity to fix P was reduced by 78% at the pH range (5 to 6) where he considered that maximum fixation by adsorption should take place. Organic soils do not fix large amounts of P (106); however, when black peat soil was leached with an alkaline solution to remove the active organic matter, its P fixing capacity increased. According to Doughty (52), the alkaline solution hydrolyzed any Fe present as hydroxide and this augmented the fixing power of the soil medium. Doughty failed to mention that Al may also be involved. Chandler's (34) study indicated that removal of Al and Fe oxides from the soil resulted in reduced P fixation. Conversely, when Davis (46) added Al and Fe to the soil, water-soluble P was significantly decreased.

In a P fixation review, Midgley (134) stated that practically all acid soils contain considerable amounts of hydrated Fe oxide which is distributed as a thin layer over the soil particles. He considered this as an ideal condition for P fixation particularly in latosols and podzols. Midgley thought that Al oxide was of less importance in P fixation because Al was usually present in smaller amounts. However, Taylor et al. (173) and Taylor and Gurney (170) suggested that a large amount of Fe-P is likely to be formed rapidly only in soils that contain very finely divided or highly reactive forms of Fe oxide or are deficient in Al, otherwise amorphous Al-P will be the principal compound formed in acid soils. Bauwin and Tyner (15) concluded from their study that reductant-soluble P exists in the soil as chemisorbed P dispersed at random in the matrix making up the soil concretions and the iron coatings of clay separates.

According to Kanwar (99), a large area in Kangaroo Island of South Australia has a very high P fixing capacity (5,000 ppm P). Most of the soils in the area had laterite or ironstone gravel which occurred throughout the profile and constituted 60 to 70% of some horizons. Removal of the reactive oxides of Al and Fe decreased P fixation considerably. A similar reduction was observed when the determination was made in the presence of chelating agents such as 8-hydroxyquinoline. Kanwar (99) found that Al oxide in these Australian soils retained P more actively than an equivalent amount of Fe oxide.

Brookfield (29) studied the P fixation of 47 acid surface soils of Australia and found a close correlation between P fixing capacity and the amount of Al and Fe extracted by ammonium oxalate (pH 3). The correlation coefficient when all soils were considered was highest between P fixation and Al. For certain groups of soils, Fe or Fe plus Al gave higher coefficients than did Al. Less P was fixed by these Australian soils after various amounts of their Al and Fe were extracted chemically.

Bass and Sieling (14) found that the amount of Al and Fe extracted by 0.5 M citric acid was a measure of the relative P fixing capacity of the soils they studied. Ramine and Metzger (156) reported that the B horizon of silt loam soils of Kansas retained more P than the A horizon especially in more leached soils. This was attributed to the accumulation of Al and Fe in the B horizon. Hance (81) defined a high P fixing soil as one that allows the soluble P to penetrate 2 to 3 inches deep and a mild fixing soil as one that allows penetration to a depth of 2 to 3 feet.

Low and Black (116) showed that P fixation by kaolinite was due to Al which was released as a result of decomposition of the clay. Russell and Low (159) found that Al-saturated kaolinite had a markedly increased P fixing capacity indicating that exchangeable Al reacted with the added P. Coleman et al. (42) reported that the P fixed by 60 subsoils from the North Carolina Piedmont region was significantly correlated with soil exchangeable Al contents. They also found that Al-montmorillonite bound quantities of P equivalent to the exchangeable Al, under conditions where Al hydrolysis was encouraged. This suggests that montmorillonite has no large inherent capacity to fix P. The data of Ellis and Truog (53) showed that free Al and Fe oxides in montmorillonite clay accounted for most of the P fixation against weak acid extraction. No appreciable P fixation against water extraction occurred when free Al and Fe oxides were removed and the clay was H-saturated.

Saini and MacLean (160) investigated the P retention capacity of 24 New Brunswick soils as related to clay, organic matter, Al, and Fe contents. On the basis of partial and multiple regression analysis, they concluded that Al had a dominant role in P fixation. Fried and Dean (67) found that Al and Fe coated exchange resins retained a large proportion of the added P. The Fe coated resin retained only slightly more P than the Al coated resin. However, in a mixed system most of the P was retained by the Fe coated resin system.

Although soil researchers agree that P fixation in acid soils is dominated largely by Al and Fe, the precise mechanism of P fixation remains a subject for debate.

Mechanism of P Fixation

There are at least three mechanisms discussed in the literature to explain P fixation in soils, namely: (a) chemical precipitation, (b) anion exchange, and (c) chemical adsorption.

Chemical Precipitation

Ford (64) in 1933 reported that the P which combined with limonite and hydrated bauxite was found by X-ray analysis to be crystalline Later in 1940, Metzger (133) concluded that in acid soils under field conditions, chemical precipitation accounted for most of the P fixation, and adsorption was probably of small practical significance. His conclusion was, in part,based on the observation that there was no equivalent replacement of P by oxalate. Ghani and Islam (75), working with acid soils in India, claimed that chemical precipitation accounted for the high proportion of the fixed P found as Al-P and Fe-P.

The surface of natural kaolinite was shown by Russell and Low (159) to be covered with Al ions or hydrous oxide films of Al which reacted with P. They concluded that the adsorbed Al precipitated P on the kaolinite surface. In 1957, Hemwall (85) in a review regarding P fixation in soils stated that it was unlikely that the formation of $AlPO_4$ and $FePO_4$ accounted for much fixation but rather the compounds formed were Al and Fe oxy- and hydroxyphosphates [(Al or Fe) $(H_2O)_3$ $(OH)_2H_2PO_4$]. Hemwall claimed that these compounds were identified and that isomorphous substitution of Al and Fe was common. Cole and Jackson (40) reported that Al-P and Fe-P were crystalline at room temperature. They showed evidence that Al-P and Fe-P precipitated to the variscite-barrandite-strengite isomorphous series, and sterrite.

Lindsay and Stephenson (114, 115) reacted a triple point solution (TPS), a solution in equilibrium with monocalcium phosphate monohydrate (MCP) and anhydrous dicalcium phosphate (DCPA), with successive increments of soil. The reaction of soil with TPS resulted in the dissolution of Al, Fe, Mn, Ca, and other soil constituents. As successive soil increments were contacted by the TPS, the dissolution process continued and the pH of the solution increased. The solution soon became supersaturated with respect to certain phosphate compounds that slowly precipitated. With time, the precipitation of cations was in the order Fe> Al> Mn. Most of the filtrates obtained from the reaction of soil with TPS precipitated solids upon standing. Some of these solids were identified as crystalline Al-P, Fe-P, or Ca-P.

Taylor *et al.* (173) believed that Al hydroxide was the principal agent in the precipitation of phosphate from P fertilizers in acid soils. They reported that under moist soil conditions, amorphous Al-P was probably the principal product formed while under relatively dry conditions, dicalcium phosphate may be formed also and a mixture of Ca-Al-phosphate may finally result. Potassium and NH_4 are also involved in phosphate precipitation. Taylor and co-workers (170, 171) found that when P solution was reacted with Al hydroxide in the presence of K and NH_4, these cations were precipitated as taranakite.

Anion Exchange

Anion exchange reaction may be visualized as the substitution of one anion by another which is present in solution in greater concentration or possesses a stronger tendency to hold its position in the soil.

In 1937, Scarseth (17) suggested that the principle of an equivalent anion exchange may explain P fixation in soils. Later, Coleman (41) showed that although the free Al and Fe oxides present in montmorillonite and kaolinite clay minerals were responsible for P fixation, the small amounts of Al and Fe oxides soluble at any given time did not account for the large amount of P fixed by the clays. According to Coleman (41) and Kelley and Midgeley (100), evidence for anion exchange was the observed increase in pH of the clay-phosphate system after P fixation had occurred. They explained that the increase in pH was brought about by the exchange between the phosphate ions in solution and the hydroxyls from the clay mineral or hydroxides of Al and Fe. Kelley and Midgeley (100) stated that anion exchange was greatly shifted towards P fixation because of low hydroxyl concentration in the soil solution.

Dean and Rubins (48) proposed that the exchange between certain hydroxyl ions of the clay minerals or hydrous oxides and phosphate ions in solution could be described by the reaction,

$$\underset{\text{soil surface}}{XOH} + \underset{\text{solution}}{H_2PO_4^-} \rightleftharpoons \underset{\text{soil surface}}{XH_2PO_4} + \underset{\text{solution}}{OH^-}$$

Their conclusion was that soils have anion exchange capacities because soils could be alternately saturated with arsenate and phosphate ions. Fried and Dean (67) demonstrated that not only was P retention a function of P concentration but also 75% of the P retained by ferrated cation exchange resin was exchangeable with ^{32}P. It was considered that this rate of exchange would be too high for a precipitate.

Stout (167) reported the existence of a reversible ionic exchange between phosphate and hydroxyl ions in alumino-silicate minerals. He suggested that exchangeable hydroxyl ions were definite components of the lattice structure of clay minerals. These hydroxyls exchange only if they lie at the surface of the crystal or if the phosphate ion can reach them by entering between the individual alumino-silicate layers. Stout was able to change the crystal structure of kaolinite by P treatment. Hutjadi *et al.* (138) reported that in kaolinite at a low P concentration, phosphate binding took place with Al atoms on the periphery of the crystal. At a high P concentration (> 200 ppm P), the phosphate penetrated into some amorphous region of the clay surface. Hsu (91) was of the opinion that isomorphous substitution of phosphate for hydroxyl or silicon tetrahedron from clay minerals was a special case of decomposition-precipitation process.

Chemical Adsorption

Hsu (90) defined P adsorption as a process in which P was chemically held on the surface of amorphous Al hydroxides or Fe oxides. Hsu (90, 91) emphasized that physical adsorption was not significant in the fixation of P.

It was established by several workers (83, 90, 91, 92, 93, 192) that there are two reaction steps in P fixation. The first reaction occurs very rapidly, and is practically completed within 30 minutes. This is followed by a slow rate reaction which reaches equilibrium over a long period. The fast reaction is considered primarily as a chemical adsorption process and the slow reaction a decomposition-precipitation reaction. With time, the P adsorbed is precipitated through a decomposition-precipitation process which ultimately results in the formation of crystalline products.

Laboratory studies showed that P fixation by soils followed the Langmuir and Freundlich adsorption isotherms (92, 93, 138, 143, 192). However, this was not accepted as conclusive proof that P fixation was an adsorption process. Hsu and Rennie (92, 93) and Woodruff and Kamprath (192) discussed the limitations of the isotherms as applied to P fixation studies in soils.

Mattson et al. (122) and Kittrick and Jackson (103) suggested that chemical adsorption and precipitation were basically the same mechanisms; both mechanisms resulted from the attraction between Al or Fe and P. On the other hand, Hsu (90) viewed adsorption as a special case of precipitation in which Al or Fe remained as the constituent atom of the corresponding hydroxides or oxides but reacted with P by virtue of its residual reaction force on the surface.

Hsu (91) reported that pH greatly affects the type of P fixation process in the soil. In acid medium (pH 4), P fixation is essentially a precipitation reaction. In slightly acidic to neutral medium (pH 6 to 7), amorphous Al hydroxides are stable and P is adsorbed on the surface. The two processes, adsorption and precipitation become indistinguishable when Al hydroxide species of intermediate size are present. Precipitation occurs when P breaks only part of the Si-O-Al or Al-OH linkages leaving Al or Fe still in the lattice, identical to isomorphous substitution. Whether the interchange between a hydroxyl ion and a phosphate ion is properly called as anion exchange or an adsorption process still appears to be a matter of opinion.

Phosphorus Fractions and Their Availability to Plants

Phosphorus in the soil may be broadly classified as inorganic and organic P. The inorganic P consists of five main groups of compounds: water-soluble P, Ca-P, Al-P, Fe-P and reductant-soluble P. The soil organic P fractions which have been identified are phospholipids, nucleic acids, and inositol phosphates. These fractions constitute about 40 to 50% of the organic P (174).

Inorganic P Fractions in Soils

It was not possible to fractionate principal chemical forms of P in the soil discretely until Chang and Jackson (36) published in 1957 their soil P fractionation scheme. In this method, 1 $\underline{N}$ NH_4Cl, neutral 0.5$\underline{N}$ NH_4F, 0.1$\underline{N}$ NaOH, and 0.5$\underline{N}$ H_2SO_4 solutions were designed to extract water-soluble P, Al-P, Fe-P, and Ca-P, respectively. The portion of P not extracted by the above solutions was completely dissolved by the dithionite-reduction chelation procedure, and thus called the reductant-soluble P. A solution of 0.5 $\underline{N}$ NH_4F at pH 8.5, according to Fife (59), was a better extractant of Al-P than at pH 7.

The amount of water-soluble P in the soil is usually very low (36, 88, 197). Most of the soil inorganic P before or after the addition of P fertilizer is found in the Al-P, Fe-P, Ca-P, and reductant-soluble P fractions. In seven virgin soils of Kansas, it was reported by Bhangoo and Smith (18) that Al-P and Fe-P accounted for more than one-half of the total P in the surface soil and about two-thirds in the subsoil. MacKenzie and Amer (118) increased the Al-P fraction of acid soils at two rates (200 and 2,000 kg/ha) of added P, increased Fe-P only at the higher rate, and did not change the amount of Ca-P at either rate. Native and residual P in latosols of Hawaii existed predominantly as Fe-P and the application of P fertilizer resulted in a small amount of Al-P and little Ca-P (84). Soil P in the West Indies was present mainly as Fe-P (2). Even in alkaline soils, as much as 8 to 40% of the total soil P was present as Al-P and Fe-P (144). In acid sandy soils, Al-P and Fe-P were the major inorganic P fractions (87, 88, 197).

Some soils in Indiana were found by Al-Abbas and Barber (3) to contain largely occluded P. According to Robertson (151), Al-P converted to Fe-P and occluded P with passage of time. After 8 to 13 years of cropping, Robertson accounted for most of the applied P in the occluded P fraction. Shelton and Coleman (163) found a decrease in Al-P with an increase in Fe-P over an 8-year period. Reductant-soluble P occurred 3 and 5 years following the application of 1,371 and 685 kg P/ha. Shelton and Coleman (163) proposed a method of investigating long term field equilibrium conditions in a relatively short period by incubating the soils in boiling water. Their results showed a greater decrease in Al-P than the increase in Fe-P but the reductant-soluble P accounted for most of this loss. Godfrey and Riecken (77) reported that soil weathering tended to transform Ca-P to Fe-P and Al-P.

Relative Availability of Inorganic P Fractions

In general, the reductant-soluble P is unavailable to plants (173) while the other inorganic P fractions are relatively available. Bailey (10) concluded that in addition to organic P, Al-P, Fe-P, and Ca-P were available to plants in the tropical soils of Sarawak. A comparison of the inorganic P fractions in the soil before and after growing three crops of alfalfa (*Medicago sativa* L.) by Singh *et al.* (165) provided evidence that Al-P, Fe-P, and Ca-P were sources of P to the first crop and that Fe-P was the main source to the second and third crops. The decrease in the ratio of Al-P to Fe-P with time was reported by Robertson (151) to be due in part, to P uptake by plants.

Halstead (80) found in his study with several Canadian soils that the Al-P fraction was correlated with the percent yield increase of oats over the control treatment. Neither Fe-P or Ca-P was related to yield. Water soluble P was correlated with both percent yield increase and percent P uptake. MacKenzie and Amer (118) leached with water, soils which were treated with P about a year before, and were able to remove P from all three inorganic P fractions. At or below pH 7.1, leaching decreased the Al-P fraction proportionately more than Fe-P. Above pH 7.1, Ca-P decreased proportionately more than the other two fractions. In an earlier work, MacKenzie's (117) isotopic exchange data indicated that Al-P was in equilibrium with water-soluble P. Furthermore, his solubility studies with 0.01 M

$CaCl_2$ showed that in most soils, the Al-P fraction supplied most of the P to the solution. In one soil, Fe-P appeared to supply a significant amount of P to the soil solution.

Taylor *et al.* (172) evaluated several complex Al-P and Fe-P minerals as sources of P for plants under greenhouse conditions. The P uptake from the Ca-ferric phosphate was between 80 and 90% of that from similar applications of monocalcium phosphate, while acidic K-ferric phosphate proved to be unavailable. The same workers reported that K taranakite, colloidal Al-P, and colloidal Fe-P were relatively good sources of P and should not be regarded as factors responsible for P fixation. The availability of P to sudangrass (*Sorghum sudanense* Stapf.) in sand culture experiments was found by Juo and Ellis (98) to be in the order colloidal Al-P = colloidal Fe-P> variscite >strengite. Juo and Ellis also found that the availability of P from different compounds in the soil was controlled by the specific surface area and degree of crystallinity of the compounds. Because of smaller particle size, greater surface area, and amorphous structure, the colloidal forms of P compounds were readily available to plants. As crystallization occurred with passage of time, the availability of P decreased. Aluminum P crystallizes over a much longer period than Fe-P and this perhaps explains the findings that native Al-P tends to be more available to plants than Fe-P.

Iron P and reductant-soluble P are probably the major P sources in soils under conditions which encourage Fe reduction. Chang and Juo (38) reported that Fe-P was the main source of P in many flooded rice fields in Taiwan. Ahmad (2) found that upon submergence and development of anaerobic condition in the soil, reductant-soluble P decreased.

The available P content in a puddled soil at planting, according to Basak and Bhattacharya (13) was about 2.4% of the total P content and increased to 64% at tillering in addition to the P taken up by the growing rice (Oryza sativa L.) plants.

Organic P Fractions in Soils

The amount of organic P varies widely with soils and generally represents a considerable amount of the total soil P. Basak and Bhattacharya (13) reported that rice soils contained 42% of the total P in organic form. Some Costa Rican soils had 52% (26), Nigeria forest and savanna soils had 43 and 18% (56), respectively, and calcareous soils from Colorado contained 23% organic P (79). In Australia, soil organic P varied from 6 to 1,773 ppm P (191).

According to Larsen (109) organic P comprises between 20 and 80% of the total soil P and the proportion of this organic P in solution is small. The highest reported value for phospholipids was only 34 ppm P and usually did not exceed 3 ppm P (174). Tisdale and Nelson (174) stated that in 49 Iowa soil samples, inositol hexaphosphate accounted for an average of 17% of the total organic P with a range of 3 to 52%. In a group of Australian soils, the total amount of inositol pentaphosphate and inositol hexaphosphate varied widely ranging from 1 to 356 ppm P and accounted for 0.4 to 38% of the total organic P (191).

Mineralization and Availability of Organic P

The organic P content of a soil at any given time results from the net effect of mobilization and immobilization processes (106). The turnover of organic P is largely a biological process and it is strongly affected by the chemical, physical, and biological properties of the soil. The mineralization of soil organic P depends, among other things, on the organic P content of the organic matter in relation to microbial demand (55). It was considered that mineralization of organic P occurred when the C/organic P ratio was less than 200 and immobilization if the ratio was greater than 300 (174). Enwezor (55), however, reported that a C/organic P ratio was not a reliable index for predicting P mineralization. He found that whereas P mineralization occurred at a C/organic P ratio of 578 (48% organic P) there was immobilization at lower ratios of 41 (28% organic P) and 34 (36% organic P) In the Soviet Union and several eastern European countries, soils were innoculated with phosphobacterin (*Bacillus megatherium* var. *phosphaticum*) to increase the availability of native and applied P (174).

Synthesis as well as breakdown of organic P also occurs in the soil. Weir and Black (185) cited various instances where organic P may actually increase. The application of superphosphate to permanent pasture in New Zealand increased the organic P in addition to increased organic C and N in the soil. In Japan, organic P in cropped soils was higher than in virgin soils, and this increase in organic P was associated with fertilization and accumulation of total P in the surface soil. Similarly, in Finland, the application of inorganic P as fertilizer to organic soils in field experiments increased the organic P content of the soil in most instances.

The amount of P mineralized from organic forms varies widely depending on the soil conditions. Basak and Bhattacharya (13) reported that as much as 132 kg/ha of P may be mineralized during one rice cropping season. The average organic P mineralized was 3.6 ppm in 13 Colorado soils incubated for 21 days at 35C (79). Manning and Solomon (120) found that organic P decreased in the order of 301, 197, 173, and 128 ppm when 0, 186, 718, and 1,810 ppm P were applied to the soil, respectively. McCall et al. (125) showed that incubation of eight organic soils from Michigan and Florida for a few months decreased organic P from an average of 515 ppm initially to 152 ppm in control samples and to 25 ppm where 200 ppm P as Ca $(H_2PO_4)_2$ were applied to the soil. The enhancement of soil organic P mineralization by incubation with added inorganic P, however, could not be reproduced by Weir and Black (185) except when the P was added in an acidified solution.

The solubility curves of Ca phytate and other organic P compounds indicate that these compounds are partially acid soluble (20). Bishop and Barber (20) suggested that acid-hydrolyzed organic P influenced the total P available to plants. Jackson and Black (95) found that the solubility of inositol phosphates of Al, Fe, Ca, and Mg ranged from less than 1 to 30% of the solubility of inorganic P compounds. This would indicate that the value of these organic P compounds as sources of P for plant growth is relatively low. Phytin and lecithin were absorbed directly by plants from nutrient solutions with the rate of uptake of phytin approaching that of KH_2PO_4 (155). On the other hand, nucleic acid, nucleotide, and Ca glycerophosphate were decomposed to inorganic P before P absorption. Decomposition was brought about by enzymes present in a gel-like material adhering to the root surface (155). This suggested that soil organic P would not necessarily have to be water soluble to be of value to plants

Soil-Plant Relations in P Uptake

Phosphorus uptake by plants was divided into four stages (70): release of P from the solid phase into the soil solution, the movement of P from any point in the soil solution to the vicinity of the root, movement of P from the vicinity of the root into the root, and movement of P to the top of the plant. Each of these steps involved rate constants which were controlled by factors of either soil or plant.

At any instant during plant growth in the soil, there is a given supply of P to the plant. If the plant absorbs nutrients only from the soil solution, the instantaneous supply is the amount in the soil solution which is considered as the intensity factor (69, 70). The soil solution must be renewed many times during the day to meet the requirements of plants. Russell (158) stated that about 0.2 kg/ha of P was in the soil solution, however, plants may take up 10 to 20 kg/ha of P during the growing season. Fried and Shapiro (69) reported that in eight soils studied, the P in solution must have been renewed 1.3 to 1.7 times/hour in order to account for the total P absorbed by plants. If the rate of uptake was not uniform, then the rate of turnover must have been higher during certain growth periods. The ability to renew the P in solution was taken as the capacity factor (69, 70). The relationship between the intensity and capacity factors distinguishes the P system in one soil from the P system in another.

According to Russell (158), the P concentration in many soil solutions remains approximately constant while a plant is growing in it. Fried et al. (68) showed that for two acid soils and one calcareous soil, moderately supplied with P, the rate at which P was absorbed by plants was less than the rate of P going into solution by a factor of at least 250. Fried and Shapiro (70) cited the work of others which showed that the movement of phosphate ions to the solution-root interface was brought about mainly by soil water movement (mass-flow) that overwhelmed the diffusion of ions under a concentration gradient. However, Barber and Olson (12) reported that almost all of the P absorbed by a corn plant from a typical fertile silt loam was supplied by diffusion and only a small amount by root interception and mass-flow.

Lewis and Quirk (113) studied the P depletion patterns around wheat roots under controlled environment in a soil to which various amounts of P had been added (100 to 1,000 ppm P). At all levels of P, the zone of depletion was similar in size extending approximately 1 mm from the surface of the root. Numerous root hairs found on the roots suggested that the root morphology influenced the size of the depletion zone more than the diffusion rates within the soil. Depletion was envisaged as occurring radially towards the root hairs and parallel to the main root cylinder.

Altering the P supply of a soil by fertilization can cause changes in the total amount of P absorbed and the P concentration in the plant. Depending on the amount of native soil P, an increase in the supply of P may result in a higher, lower, or unchanged concentration of P in the plant (48). Under conditions where increasing the P supply resulted in no or relatively small growth changes, an increase in P supply usually was accompanied by an increase in both the P concentration and total P uptake (48). In areas of similar soils and climate, it was shown that analysis of a particular plant part at a definite stage of growth gave useful information regarding the changing P supply of soils (119).

Measurement of Available P

Baker (11) defined "availability of P" as the readiness with which a small percentage of the total soil P moves into growing plants and "available P" as the amount which moves from the soil to plants over a long period of time. Trung (176) suggested that the designations of "readily available" and "difficultly available" be used rather than "available" and "unavailable" when speaking about the soil P in relation to its availability to plants. His reason was that plants may obtain some P from even the most difficultly available soil P compound.

The estimation of plant available P has been the concern of soil and plant scientists for a long time, however, no single method can be used universally to obtain an invariably satisfactory result. This has necessitated the development of numerous techniques of measuring available P. The procedures have been grouped into several categories: biological, chemical extraction, anion-exchange resin, and isotopic dilution methods (11, 110, 141).

The methods involving the use of microorganisms and higher plants to measure the amount of available P in the soil were reviewed by Nelson *et al.* (141). The microorganisms which have been used as biological indicators are *Aspergillus niger*, *A. oryzae*, *A. flavus*, *Azotobacter* sp., *Cunninghamella blakesleeana*, *Cladosporium herbarum*, and *Stichococcus* sp. The field plot technique is the oldest method but it is not adapted to extensive application. However, Russell (158) warned that measurement of the soil P status in the laboratory or greenhouse must be used with great caution for predicting field responses because of the difference in soil volume tapped by the plant root system with the two techniques.

Fried and Dean (66) introduced the "A" value and presented the concept that a plant having two sources of a nutrient will absorb its nutrient from each of these sources in direct proportion to the amounts available. This is done by use of standard ^{32}P and the following expression:

$$A = \frac{B(1-y)}{y}$$

where A is the amount of nutrient available in the soil, B is the amount of nutrient in the standard, and y is the proportion of the nutrient in the plant derived from the standard.

Chemists have devoted a great deal of time devising chemical methods because they are more convenient to use. Some of the earlier extracting solutions included water, CO_2-saturated water, and 1% citric acid (141, 158). Numerous extracting solutions have been developed ranging from mineral acids and bases to buffered solutions of various pH (19, 141, 149, 158). The relative value of different extractants in evaluating the availability of P has been shown to vary with soil, plant species, and climate (11, 141).

Weir (183) evaluated several P soil test methods for some soils of Jamaica. The methods included those of Truog (0.002 $\underline{N}$ H_2SO_4, pH 3), Bray (0.05 $\underline{N}$ NH_4F + 0.1 $\underline{N}$ HCl), Olsen (0.5 $\underline{M}$ $NaHCO_3$, pH 8.5), Morgan (10% NaAc + 3% HAc), and Saunder (0.1 $\underline{N}$ NaOH, hot). The relative efficiency of estimating the available P of the soils was found to be in the following order: Truog > Bray > Olsen > Morgan > Saunder. Saunder (161), however, reported that his method was good for determining the available P of tropical soils, particularly red earths.

Welch *et al.* (186) showed that either of the three soil test methods, North Carolina (0.05 $\underline{N}$ HCl + 0.025 $\underline{N}$ H_2SO_4), Olsen, and Bray and Kurtz (0.03 $\underline{N}$ NH_4F + 0.1 $\underline{N}$ HCl) could be used satisfactorily as a basis for making P recommendations for three soil types in Alabama. Leamer (112) studied the response of alfalfa to P fertilizer applications in P deficient reddish brown soil during a period of eight years. Alfalfa yields were closely correlated with both percent P in the plant and $NaHCO_3$ extractable soil P during the first four years. High yields were maintained in the second cycle of the rotation but percent P in the plant and $NaHCO_3$ extractable soil P were at levels associated with low yields during the first cycle.

Miller and Axley (135) reported that although there was little difference in the correlation coefficients of the various chemical methods they studied, their method (0.03 $\underline{N}$ NH_4F + 0.03 $\underline{N}$ H_2SO_4) showed the closest relationship with crop response. Several of the chemical methods extracted 1.5 to 3 times more P from rock phosphate treated soils than from those treated with the same quantity of P from superphosphate, yet the yields of corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and clover (*Trifolium repens* L.) were less from the rock phosphate treatment. Al-Abbas and Barber (4) found that shaking 1 g of soil with 20 ml of solution (17 ml 0.3 $\underline{N}$ NaOH + 3 ml 0.5 $\underline{N}$ $Na_2C_2O_4$) was satisfactory as a soil test for P particularly on soils of pH above 7.

According to Susuki et al. (169), Truog solution removed portions of both Al-P and Ca-P while the Bray solution primarily removed Al-P. Ammonium flouride solution at pH 8 did not dissolve P in apatite form but it may have removed other forms of Ca-P like mono- and dibasic Ca-P. Westin and Buntley (187) reported that the Olsen method increased the solubility of Ca in calcareous soils as a result of two processes: (a) the repression of Ca activity (common ion effect of $CO_3^=$ ions in the presence of solid phase $CaCO_3$) and (b) replacement of phosphate ions by HCO_3^-, $CO_3^=$, and OH^- on the surface of soil particles. In acid and neutral soils, the main effect was through the replacement of phosphate ions.

The threshold soil P levels as determined by various chemical extractants at which plants may or may not respond to P fertilization vary widely. Saunder (161) found that with soils from southern Rhodesia, the threshold levels of 0.1 N NaOH-extractable P below which appreciable crop responses to applied P occurred were about 80 ppm in sandy soils and 110 ppm in fine textured soils. Truog (176) reported that the minimum limits of 0.002 N H_2SO_4-extractable P in Wisconsin were about 32 and 22 kg/ha of P in fine and coarse textured soils, respectively. McGeorge (126) extracted P with 1% citric acid from Hawaiian sugarcane soils and found the minimum limit of readily available P to be 35 kg/ha in the plowed layer. When the 1% citric acid method was proposed, however, the minimum limit was set at 40 kg/ha of P (176).

Miller and Axley (135) showed that P applications often failed to increase alfalfa and wheat yields in pot culture experiments when the levels of extractable P in the soils for the various chemical methods were Truog and Bray-Kurtz, 55 kg/ha, and Olsen and Miller-

Axley, 70 kg/ha. The threshold values in organic soils at which plant yields were not increased with additional P applications were reported by Larsen *et al.* (107) to be 10 and 16 kg/ha of water-soluble P when the soil-water suspension was shaken for 2 and 30 minutes, respectively.

Lathwell *et al.* (110) developed a percolation method involving the use of an anion-exchange resin for continuous extraction of P from soil samples. A modification was also investigated where the soil was directly equilibrated with the resin. The amount of P extracted by the resin exchanger when compared with various chemical methods gave the highest degree of correlation with crop response data, particularly P uptake.

Isotopic dilution techniques have been used to determine the available P in the soil with some success (11, 169). The measurement of available P by isotopic dilution requires that the ^{32}P approach equilibrium with the available P of the soil. The quantity of "active solid phase P" (native and applied P which equilibrates with ^{32}P) was found by Baker (11) to be a satisfactory index of available P.

Effect of Lime on P Availability

The effect of lime on the availability of applied and native soil P has been discussed extensively and has been a center of research activity by many plant and soil scientists. Whether liming of acid soils directly increases P availability is not certain. There is no conclusive proof that lime per se increases P availability to plants, although it has been claimed that it increases P availability. It seems appropriate, therefore, that both the theoretical and applied research considerations should be reviewed closely in order to understand the principles of liming and its effect on P availability to plants.

Basic Studies on the Relationship Between pH and P Availability

Plants absorb P in the orthophosphate forms, $HPO_4^=$ and $H_2PO_4^-$, with $HPO_4^=$ to a lesser extent (158, 174). The kind of phosphate ion present varies with the pH of the solution (31, 158, 174). Above pH 7, the relative concentration of the divalent is greater than that of the monovalent ion. According to Russell (158), the proportion of the phosphate ion in solution as $HPO_4^=$ at 18C was approximately 0.6 at pH 5.0, 6 at pH 6.0, 39 at pH 7.0, 86 at pH 8.0, and 98% at pH 9.0, the remainder was almost entirely $H_2PO_4^-$. The proportion of H_3PO_4 and $PO_4^=$ was negligible in this pH range.

In soils, the presence of cations complicate the simple aqueous solution system of P. At low pH, the higher activities of Al, Fe, and Mn tend to precipitate P especially at pH below 5 (31, 174). Likewise, at pH above 7, Ca and Mg and their carbonates react with P to form compounds of low solubility (31, 158). It appears then that the intermediate pH range of about 5.5 to 7 is most satisfactory in maximizing the amount of P in solution (31, 158, 174).

There is evidence that the ionic activities of Al and Fe in the soil solution are not involved in P fixation but rather the activity of surfaces of solid phases associated with Al and Fe (35) especially in the pH range of 6 to 7 (42, 91, 92, 93). Coleman *et al.* (42) added various amounts of $Ca(OH)_2$ to Al saturated montmorillonite in the absence of free electrolytes to obtain different pH values and various degrees of Al hydrolysis. Their results showed that the quantity of P sorbed was critically dependent upon the extent of neutralization. At pH 3.5, the P bound was equivalent to 24% of the exchangeable Al. At pH 5 and 7, the percentages were 70 and 97%, respectively. Hsu and Rennie (92) found that amorphous Al hydroxide can adsorb a large amount of P from solutions of varying concentrations and acidity. As mentioned earlier, in slightly acidic to neutral medium, amorphous Al hydroxides are stable and P is adsorbed on the surface (91). The rapid reaction of P fixation at pH 7 was considered by Hsu (90) to be due to the surface reactive amorphous Al hydroxides and Fe oxides present in soils. Indeed, the P retained by limed acid soils was found to be primarily Al-P and Fe-P (63, 88, 197). Buckman and Brady (31) did not rule out the possibility that even at pH 6.5, P could be precipitated by Al and Fe. Chang and Jackson's (37) calculations based on the solubility product principle showed that soluble P could be fixed by chemical precipitation involving Al and Fe in neutral soils. The same workers claimed the formation of Al-P and Fe-P in a chernozem of pH 7.5 and other neutral soils.

The acidic solution (TPS, pH 1.01) produced by a dissolving P fertilizer particle adds another complicating factor. The TPS decreases the pH of the soil with which it comes in contact and destroys crystalline precipitates of Al hydroxide, Fe oxide, and clay minerals bringing Al, Fe, Mn, and Ca into solution to be precipitated as insoluble P compounds (114, 115).

Lime does not change the relative distribution of different P fractions in the soil, consequently the solubility of soil P remains the same. Pratt _et al._ (147) found that where the soil had been alkaline for many years, a Ca-P type solubility curve was indicated.

Where the soil had been acid, the Al-P or Fe-P type solubility curve was obtained. Where the soils were changed from acid to alkaline or alkaline to acid for only a few years, the P solubility curves did not change.

Ford (64) reported that lime does not have a consistent effect on P fixation because it was more effective in reducing P fixation in some soils than in others. Woodruff and Kamprath (192) reported that neutralization of acid soils (pH 4 to 4.8) reduced their P adsorption maxima while liming slightly acid soils (pH 5.2 to 5.9) had very little effect. The amount of sesquioxide and residual soil P may also explain some of the variant effects of liming. Investigation of several West Florida soils by Robertson *et al.* (153) revealed that liming soils low in residual P to pH 6.5 increased the availability of applied P to plants when the amount of sesquioxides was high but had no effect where the sesquioxides were low. Liming soils high in residual P reduced the availability of fertilizer P regardless of the sesquioxide content because of increased availability of residual P

According to Calvert *et al.* (33), H saturated clays (fresh acid washed) retained more P with increased Ca saturation, whereas H-Al saturated clays (aged acid washed) generally decreased beyond some value of Ca saturation (20%) after an initial rise in P retention. It was theorized that the addition of the first increment of $Ca(OH)_2$ neutralized the exchangeable H which in effect increased retention, while neutralization of Al decreased P retention. Ragland and Seay (150) found that at Ca saturation values greater than 60%, there was an increase in both P retention and P fixation against 0.005 *N* H_2SO_4.

Phosphorus retention was considered to be due to the formation of P-Ca-clay bridges which were not broken by acid extraction. However, Truog (177) believed that P linked to Ca was available to plants because it was easily extracted with carbonated water or other weak acids. Other investigators have reported that liming may result in the formation of relatively insoluble Ca-P compounds like hydroxyapatite (63, 153) or fluorapatite under field conditions (139).

In acid sandy soils, P leaching may be a problem and better yields obtained by liming may be due, in part, to increased retention of P fertilizer in the soil. Neller et al. (140) reported that 91% of applied P was leached from acid sandy soils (pH 4.6) in Florida while only 70% was leached from limed soils (pH 5.6). At the end of a 15-year period during which 1,550 kg/ha of P were applied, Spencer (166) found the highest concentration of total P in the surface 6 inches in limed soil, while in unlimed soil, the P concentration was highest in the 12- to 36-inch depth, leaving the surface soil deficient in P.

Data were reported that liming acid soils to neutrality increased P solubility in various chemical extractants and this was taken as evidence that liming increased the availability of P to plants. According to Truog (177), Dehérain in 1892, described an experiment which showed that treatment of Fe-P with $CaCO_3$ caused a transformation such that some of the P became soluble in carbonated water and thus available for plant use. Truog (177) conducted a simple test to demonstrate that difficultly available soil P becomes soluble in weak acid rather rapidly by liming an acid soil to pH 7. He applied 5 levels of lime to two acid soils (pH 4.6) to increase the pH to near neutrality (pH 6.7). The soils were incubated for 110 days under moist condition. His data showed that lime increased markedly the amount of P dissolved in 0.002 *N* H_2SO_4 in every case and the greatest increase took place near the neutral point. Boiling the lime treated soil samples with water gave nearly the same results as the incubated samples.

Effect of Lime on P Content and Yields of Crops

Many investigators have reported that the increase in availability of native and applied P brought about by liming the soil is reflected in increased dry matter yields and P concentrations in plants. Truog (177) presented data showing that both the concentration and dry matter weights of alfalfa were increased by liming a soil from pH 4.9 to 6.9. Taylor *et al.* (172) reported that liming Hartsells fine sandy loam from pH 4.8 to 6.3 increased corn growth significantly. In Florida, Robertson *et al.* (152) found that less fertilizer P was needed to obtain maximum yields of peanut (*Arachis hypogaea* L.) on limed than unlimed Red Bay fine sandy loam. Hortenstine (87) showed that in Lakeland fine sand, there was a linear increase in foliage yields of oats (*Avena sativa* L.) with the amount of lime applied. An investigation by Albrecht and Klemme (5) revealed that Korean lespedeza (*Lespedeza stipulacea* Maxim.) contained twice as much P when grown on a soil treated with superphosphate and lime as when grown on the same soil treated with superphosphate alone. The result of Awan's (8) field experiments in Honduras showed that yields of corn, sorghum (*Sorghum vulgare* Pers.), and cowpea (*Vigna sinensis* L.) were increased significantly when a slightly acid soil (pH 5.5) was limed to pH 6.5. The highest yields were obtained from plots receiving both lime and P.

Truog (177) showed data from one soil (pH 5.9) where plant yields were increased markedly by lime applications through pH 7.4. He interpreted this to mean that pH 5.9 was not high enough to make notable amounts of P available to plants. Blanco et al. (21) found that the optimum pH for wheat when fertilized with superphosphate and triple superphosphate was about 5.4 and for the natural phosphates, 4.7 to 5.3. Increasing the pH higher than 5.5 by liming decreased the efficiency of P fertilizers. Robertson et al. (153) reported that liming above 6.5 caused the percent P in the plant from the fertilizer to level off or decline. They speculated that relatively unavailable tricalcium phosphate was formed. Liming red and yellow podzolic soils of Puerto Rico did not change significantly the amount of P absorbed by plants from applied fertilizer (25).

Lime has a favorable influence on many soil fertility factors which often cannot be distinguished from its effect on the availability of inorganic P. Some of the soil factors are nitrification, mineralization of N and organic P, correction of toxicity of metals like Al, Fe, and micronutrients, and increased Ca or Mg supply in the soil.

Bear (16) concluded that the direct effect on P availability produced by liming acid soils is probably less than the indirect effect produced by creating more effective conditions for increased production of plant residues and increased activity of microorganisms. Awan (8) attributed the increase in crop yields caused by liming to organic P mineralization because he found the amount of soil organic P to be reduced in limed soil after 2 years of cropping.

The acid soils used by Hortenstine (87), Robertson and co-workers (152, 154), and Awan (8) contained low amounts of Ca. Plants grown on these soils may have responded to the addition of lime because of Ca. Davis and Brewer (47) reported that liming soils low in Ca enabled Austrian winter peas (*Pisum arvense* L.) and common vetch (*Vicia sativa* L.) to utilize larger quantities of P and N.

Abruña-Rodriguez and Vicente-Chandler (1) reported from Puerto Rico that sugarcane yields increased from 25 to 100 T/ha where the exchangeable Al was decreased from more than 8 to less than 2 meq/100 g of soil by liming. Finck (60) found a marked decrease in uptake of Al, Fe, and Mn by oats when alkaline P fertilizers were applied to the soil while the reverse was true when superphosphate was used. The data of Brown *et al.* (30) indicated that liming decreased significantly the concentration of Mn in sugar beet (*Beta vulgaris* L.) leaf blades. In general, the micronutrients (Fe, Mn, Zn, B, and Cu) are more available to plants under acid soil conditions (31).

Estrada and Cummings (57) showed that application of lime resulted in increased root growth in acid A_2 horizon of Norfolk loamy sand containing relatively high exchangeable Al. It appeared that lime increased P uptake by encouraging root proliferation which ensured greater root-soil contact.

Recently, the experiment conducted by Medappa and Dana (130) revealed some interesting relationships between P accumulation in cranberry (*Vaccinium macrocarpon* L.) and H, Ca, Al, and Fe ion activity on P accumulation by the plants between pH 3 and 7. However, at pH 8, P accumulation was depressed. Calcium concentration (0 to 750 ppm) and Fe concentration (0 to 50 ppm) had no appreciable effect on the uptake of P. Phosphorus absorption tended to increase with the addition of 1.2 ppm Al but decreased with 12 ppm or more. The decrease in P accumulation in the presence of Al was more pronounced at pH 6.5 than at pH 3.5 to 4.5. Medappa and Dana suggested that at high pH, Al-P precipitated both inside and outside the root tissue thereby impaired P accumulation.

In the tropics, according to Ignatieff and Lemos (94), crops do not always respond to lime at pH values which would give response in temperate regions. They explained that Ca displaces K, Mg, and some micronutrients from the soil. These displaced elements are finally leached to deeper layers adversely affecting the Ca/K and Ca/Mg ratios. The same workers found that lime depressed yields when applied on red-yellow podzolic soils at moderate level but not if Mg, K, and minor elements were supplied. Lime most likely lowers the uptake of micronutrients by decreasing their availability rather than by enhancing leaching.

Pierre and Browning (145) were able to correct the injury caused by lime by substituting increasing amounts of $MgCO_3$ for $CaCO_3$ up to 75%. Truog et al. (179) found a greater increase in P content of pea seeds by increasing the Mg supply in the soil rather than by increasing the supply of available P. Their theory was that Mg functioned as a carrier of P.

Lime does not have the same effect on different crops and sometimes may aggravate P deficiency in soils containing low amounts of P. Hortenstine and Blue (85) reported that P availability was reduced by liming a Pulatan loamy fine sand from British Honduras as measured by P contents of oats, sorghum, and pangolagrass. However, The P content of tomato plants (*Lycopersicon esculentum* Rutgers) increased as the amount of lime applied increased. Chin *et al.* (39) found that while yields were not affected, the P concentration in wheat was significantly decreased by lime application only at extremely high rates. Under such conditions, the P concentration in wheat dropped from 0.29% with no lime to 0.21% with lime. In the case of alfalfa, there were no significant differences in P concentration due to the various liming treatments. However, the dry matter yields were directly proportional to rates of lime up to 100 T/acre. Hardy (82) showed that liming 15 West Indian volcanic soils low in native soil P seemed to intensify P deficiency symptoms and slightly encouraged chlorosis in plants. The data of Scarseth (162) showed that liming a soil from pH 4.9 to 6 caused a marked depression of growth of oat plants when the amount of P applied was low. However, when a large amount of P was added, lime increased plant growth.

Organic Matter as a Source of P and Its Effect on the Availability of Soil P

In areas where the use of inorganic fertilizers is economically prohibitive and fertilizers are not readily available, turning under of organic matter is usually practiced. The addition of organic matter to the soil increases the availability of P by the following processes (174) (a) action of carbonic acid which is formed from evolved CO_2, (b) formation of phospho-humic complexes which are more easily absorbed by plants, (c) coating of sesquioxide particles by humus to reduce P fixation, (d) anion replacement of the phosphate by the humate ion, and (e) mineralization of organic P. Organic material, added to the soil, may be in the form of plant residue, animal manure, or composted refuse from urban areas.

Bradley and Sieling (28) reported that organic substances from organic material decay prevented the precipitation of P by Al and Fe by forming organo-metallic molecules of these ions. Larsen et al. (108) showed evidence of negative adsorption of P induced by humic acids. This negative adsorption was diminished when Al and Fe were added to the soil.

Struther and Sieling (168) suggested that the increase in P availability attributed to liming was primarily due to the greater amount of organic anions produced in the soil as a result of stimulated microbiological activity. Their data showed that citric, oxalic, tartaric, malonic, and lactic acids were effective in preventing P precipitation by Al and Fe at various pH levels. According to Bear (16), organic anions complex Al, Fe, and Ca and thereby solubilize the relatively insoluble phosphates. This solubilization effect helps explain the frequent inability of the chemical soil test to predict the P-supplying power of a soil.

Organo-metal complexes, however, are still capable of retaining P to some degree. Weir and Soper (184) reported that the humic-acid-Fe complex was able to hold P against an anion exchange resin, the amount of P held being pH dependent. Saini and MacLean (160) found a significant relationship between P retention capacity and organic matter. They suggested that part of the Al was associated with a relatively uniform portion of the organic matter in the form of complexes which were active in P retention.

Organic matter contains very different percentages of nutrients depending on origin, storage, and degree of decomposition. This makes it difficult to interpret the results of experiments of simple design comparing the effects of organic matter and P fertilizers on plants. Besides, there are advantages derived from the addition of organic matter to the soil which are not directly related to mineral nutrition.

Fuller and Dean (71) found that at given rates of applied P, unground wheat tops incorporated into the soil were about 70% as efficient as superphosphate. Dalton *et al.* (45) added P-free starch and glucose to an acid sandy loam and found that the total P uptake in six cuttings of ladino clover and one crop of corn was practically the same as that from 78 kg/ha of P applied as KH_2PO_4. Similarly, White *et al.* (188) demonstrated that alfalfa green manure was as effective in supplying P as KH_2PO_4. Fuller *et al.* (73) reported that the amount of P absorbed by rye (*Secale cereale* L.) from barley (*Hordeum vulgare* L.) residue varied from 35 to 58% of the total P content of the residue, depending upon the age of the barley. Green manure released as much as 90% of its P content, especially in soils of low P availability. Data by Fuller *et al.* (73) suggested that the threshold P concentration of the plant residue wherein P immobilization did not occur was about 0.2% P.

A large application of green manure was found by Fuller and Dean (71) to depress the growth of the first three cuttings of ryegrass. Later, after the grass recovered, about half of its P content was obtained from the organic matter. The depression in growth was attributed to the temporary immobilization of P by the microflora. However, N immobilization must have contributed a significant depressing effect. Fuller and Nielsen (72) reported that a relatively greater amount of P was utilized by plants from wheat-straw compost than from wheat straw.

The P in grazed pastures is cycled from the soil, to the animal through the plants, and back to the soil. Animal manure contains a reasonable amount of P, the percentage may vary from 0.2 to 1.2% P (43). McAuliffe and Peech (123) found that only 18% of the total P in sheep feces was in the organic form, most of this appeared in the protein bound fraction. McAuliffe et al. (124) reported that, in general, manured ryegrass contained a higher percentage of P than that fertilized with superphosphate. However, the P from superphosphate was somewhat more available than that from manure, particularly in the first cutting. With time, there was little difference in availability between the two sources of P.

Martin (121) proposed that the reutilization of organic P compounds released from decaying plant material could contribute significantly to the P nutrition of permanent pastures. He found simple esters derived from myo- or DL-inositol to contain in excess of 200 ppm P. Evidence for additional phosphate esters occurring in soil solution was provided by experiments employing ^{32}P. Pot experiments showed that a wide range of phosphate esters, including the myo-inositol phosphates, were readily utilized by ryegrass as sources of P.

Effect of Si on P Availability

At present, the mechanism of Si participation in plant metabolism is not known and it is doubtful that any plant physiologist would place Si on the list of essential nutrient elements. However, there is evidence that Si can produce beneficial effects in plants especially in gramineous species which contain 10 to 20 times the concentration of Si found in legumes and other dicotyledons (97). Silica is known to give strength to the straw, improve plant resistance to pests and diseases, alleviate Mn toxicity, encourage the absorption of P from the soil, and increase crop yields on soils deficient in P (54, 97, 142, 158).

Silica in soil solution at pH below 9, was shown to exist almost entirely as the simple monosilicic acid, $Si\ (OH)_4$ (97, 127). It is in this form that Si is absorbed and deposited in plant tissues as opaline (97). The concentration of Si in the soil solution was shown to very greatly (2 to 375 ppm SiO_2) depending on soil pH and total Si content (136). The concentration of Si in solution increased on either side of a minimum which has been variously placed between pH 8 and 9 (97).

The specific site of action of Si in relation to P nutrition is unknown. Some workers believe that the main effect of Si is to increase the amount of P available in the soil (50, 61, 76, 102, 111, 162), while others claim that the seat of action of Si is in the plant and not in the soil (9, 65, 101).

Silica probably reduces P fixation by complexing Al and Fe or by competing against P for a place on the surface of oxides and hydroxides. The mechanism by which $Si(OH)_4$ is adsorbed on sesquioxides is obscure. Jones and Handreck (97) proposed the theory that $Si(OH)_4$ was joined through a H bond to an oxygen atom that bridged two Al (or Fe) atoms. Studies of reaction between $Si(OH)_4$ and crystalline

$Al(OH)_3$ showed that a number of layers of $Si(OH)_4$ could be formed on the surface of the hydroxide (86). Freshly precipitated hydroxides of polyvalent metal ions were found by McKeague and Cline (128) to be most effective in adsorbing $Si(OH)_4$ while some soil samples and Fe oxide minerals were moderately effective. Since it has been established that silicate ions do not exist in the soil except above pH 9, and $Si(OH)_4$ is adsorbed by sesquioxides and hydroxides, the theory of De Datta *et al.* (50) and Toth (175) that silicate replaces phosphate ions in the soil through anion exchange should be discredited.

Bilo and Smith (76) found that Si gel shaken with rock phosphate in a water suspension produced a marked increase in water soluble P. Midgley (134) cited studies by other workers which showed that Ca silicate increased the availability of P from rock phosphate while lime depressed it at the same pH. He suggested the possibility that Si assisted in a peptization of the rock phosphate particle, thus increasing its solubility. Laws (111) reported that treating the soil with Si decreased its capacity to adsorb P from solution and soil P extracted by different solutions increased with an increase in the amount of Si applied.

Scarseth (162) demonstrated that colloidal Mg and Na silicates applied to two acid soils increased the growth of sorghum. In a soil that contained abundant free $CaCO_3$, there was no evidence of increased dry matter weight except where Na silicate was added at the rate of about 6 T/ha. The combination of various Si levels with 13 ppm P, according to Albritton and Ellis (6), increased the P uptake of oats significantly when compared with the addition of P alone.

Khan and Roy (102) found appreciable release of applied P in the soil by Na silicate treatment, the effect being relatively less in a calcareous soil.

The increase in the uptake of total P by wheat and rice in a treatment with Si and without P, according to De Datta et al. (50), indicated the ability of Si to render soil P more available for plant use. Okuda and Takahashi (142) reported that at very low P levels, Si seemed to have no effect on P uptake of rice plants in culture solutions. At high P levels, Si decreased the plant P concentration. However, there was more growth in the Si treated plants when compared with the untreated plants. Rothbuhr and Scott (157) used radioactive Si to show that added P slightly depressed the amount of Si uptake by wheat while added Si enhanced the absorption of P and that a close relationship existed in their metabolism.

Khan and Roy (101) reported that Na silicate treatment markedly improved the growth and yield of jute plants (Corchorus capsularis L.) in limed and unlimed soils. The percent P in the plant was higher in the Si treatment when compared with the limed soil. In Hawaii, Fox et al. (65) were able to increase sugarcane yields by applying Ca silicate. There was little benefit from P alone. In other experiments conducted in Hawaii, yields and P uptake of sudangrass were greatly increased by Si applications (65). These benefits were believed to result from better P nutrition and decreased Al toxicity. Ayres (9) suggested that there was a level of extractable or available Si in the soil below which satisfactory growth of sugarcane would not occur regardless of nutrient supplies.

Silica is not always beneficial to plants and the effect on the absorption of P by plants may vary with time of sampling. Dawan and Hunter (51) found that Si had no significant effects upon the concentration and yields of soybeans (Glycine max L.). The P concentration of sudangrass harvested at four weeks of age was greater in plants treated with Mg and Na silicates than in those from the check soil, however, the differences disappeared after eight weeks.

Fassbender and Muller (58) studied, under greenhouse conditions, the effect of Na metasilicate on various plants in relation to different levels of P. In four soils, the application of 200 ppm Si with 86 ppm P gave a positive effect, whereas in the other four soils, the effect upon the dry weight of corn plants was negative. The dry weights of sudangrass and tomato plants were greatly reduced when the amount of Na metasilicate applied in the soil was increased to 600 ppm. However, the application of Ca-Si phosphate compound resulted in increased yields. The kind of cation in the silicate material seems to have a significant effect on the results obtained.

Recently, Silva et al. (164) reported the results of their pot experiment with 21 different plant species conducted in a humic latosol with four levels of Si at uniform P and pH. Eighteen of the 21 species had higher yields when Si was applied than when no Si was applied. The 0.65 and 2.24 T Si/ha rates gave the maximum yield for most species. Application of Si resulted in increased P concentration in 19 of the 21 species, even though 1,120 kg/ha had been applied to all treatments. Phosphorus uptake decreased due to Si application in two species, increased 6 to 20 fold in eight species, and increased 30 to 100 fold in 11 species.

MATERIALS AND METHODS

Soil Sampling

The Los Diamantes Experiment Station is located at 10°13' N latitude and 83°46' W longitude, near Guapiles, Limon, Costa Rica.

Soil samples were collected in August 1966 from a pasture area and from adjacent virgin land. The pasture area was cleared early in 1958 and planted to pangolagrass. This grass was still growing at the time of sampling. The virgin land was covered with a secondary growth vegetation of rainforest. The surface soil (0- to 15-cm depth) and subsoil (15- to 45-cm depth) were sampled separately from the same pit.

The soils were dried in a diesel fuel-heated oven to bring the soil moisture from about 55 to 30%. The soil samples were bagged in plastic-lined burlap bags. They were shipped by railroad from Los Diamantes to San Jose and by air freight from San Jose, Costa Rica to Miami, Florida. They were quarantined and fumigated with methyl bromide at the Miami International Airport. Upon arrival at Gainesville, the soils were screened (5 mm), air-dried, and stored.

The soils sampled from the virgin and pasture areas will be referred to as the virgin and pasture soils.

Soil Analysis

Soil texture was determined by the hydrometer method of Bouyoucos

(27). The techniques of Kunze (105) and Whittig (189) were followed for the mineralogical analysis of clay fractions.

Total elements were assayed by decomposing 0.1 g of finely-ground soil in 5 ml of 48% HF and 0.5 ml of 70% $HClO_4$ at 200C (96). Neutral 1 *N* NH_4OAc solution was used to determine the cation exchange capacity (CEC) and exchangeable cations in the soil (96). The concentrations of Al, Fe, Ca, Mg, Mn, Zn, and Cu in solution were determined with a Model 303 Perkin-Elmer atomic absorption spectrophotometer while K and Na were determined with the Beckman D-U flame spectrophotometer.

Total N in the soil was determined by the micro-Kjeldahl method with the salicylic acid modification of Volk and Fontain.[1] Organic C was determined by the Walkley-Black wet combustion method as modified by Walkley (181).

Soil P was fractionated by the method of Chang and Jackson (36) as modified by Fife (59). Total P in the soil was determined by the Na_2CO_3 fusion method, as described by Jackson (96), and the total organic P was analyzed by the method of Mehta *et al.* (131). The amount of available P was measured chemically by the methods of Truog, 0.002 *N* H_2SO_4 (176), Bray and Kurtz, 0.03 *N* NH_4F + 0.025 *N* HCl, as described by Jackson (96), Florida, 1 *N* NH_4OAc at pH 4.8 (149), and North Carolina, 0.05 *N* HCl + 0.025 *N* H_2SO_4 (149).

A Corning Model 12 glass-electrode pH meter was used to determine the soil pH in a 1:1 (w/v) soil-water suspension and 1:2.5 (w/v) soil-1 *N* KCl suspension.

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[1] Unpublished mimeographed sheet. Department of Soils, Univ. of Florida, Gainesville.

Results of soil analysis were calculated on an oven-dry basis (105C).

Plant Analysis

One gram of oven-dry (70C) plant tissue was ashed in a muffle furnace at 450C for 2 hours. The ash was cooled before adding 10 ml of 2:1 (v/v) concentrated HNO_3-H_2SO_4 mixture. The solution was heated gradually to 200C on a hot plate and the acids were evaporated to dryness. The residue was further heated for one hour at 450C in the muffle furnace. After cooling, the residue was moistened with 25 ml of distilled water, then 2.25 ml of 5 N HCl were added and heated on a hot plate at 80 to 90C for 30 minutes. The solution was filtered into a 100-ml volumetric flask and made to volume with distilled water. When micronutrients were included in the analysis, deionized water was used instead of distilled water.

A 10-ml aliquot was pipetted into a 50-ml volumetric flask and P was determined by the amino-napthalsulfonic acid-reduced molybdophosphoric blue color method of Fiske and Subbarrow (62).

Calcium, Mg, Fe, Mn, Zn, and Cu were determined with the atomic absorption spectrophotometer while K was determined by the flame photometer.

Results of plant analysis were calculated on an oven-dry basis (70C).

Laboratory Experiment

Two hundred grams of each of the four soil samples (virgin surface, virgin subsoil, pasture surface, and pasture subsoil) were treated with four levels of CaO to give rates equivalent to 0, 3.56, 7.12, and 10.68 T/ha of $CaCO_3$. The lime and soil were mixed thoroughly, moistened to field capacity, and incubated under laboratory conditions. Distilled water was added as necessary.

At the end of 6 weeks, the soil was allowed to reach an air-dry state. Two sets of four 1-g samples from each lime treatment were weighed into 100-ml polyethylene centrifuge tubes. In one set, the inorganic soil P was fractionated as above. The second set of samples was shaken in 50 ml of a 50 ppm P standard solution (KH_2PO_4 in H_2O) for 15 hours and centrifuged. The supernatant liquid was analyzed for P content and the P removed by the soil was used as a measure of P-retention capacity. The P-treated soil was immediately fractionated as above. The water-soluble P fraction, in this case, was not determined because the 1 N NH_4Cl extractant contained residual P solution which was physically retained by the soil (88).

Five-gram soil samples were weighed into 100-ml polyethylene centrifuge tubes. Aluminum was extracted with 1 N NH_4OAc (pH 4.8) and 0.1 N HCl by shaking for 30 minutes and centrifuging. Exchangeable Al was extracted by leaching a 10-g soil sample with 100 ml of 1 N KCl solution (129). The amount of Al in the extracts was determined by the aluminon method of Yuan and Fiskell (196). Each lime treatment was analyzed in duplicate.

Soil pH was measured electrometrically in water and 1 N KCl suspensions as above.

Greenhouse Experiments

Soil x Lime x P Experiments

Experiment I

Two and one-half kilograms of each air-dried soil were weighed into individual plastic pots, containing a 2.5-cm layer of gravel at the bottom, after the soils were limed with $CaCO_3$ at rates of 0, 5, and 10 T/ha. After 1 week, finely ground triple superphosphate was mixed with the soil at rates of 0 (P_0), 50 (P_1), 100 (P_2), and 150 (P_3) kg P/ha. The experiment was a randomized complete block with four replications.

One pangolagrass sprig was planted in each pot on 11 September 1967. The first harvest was 9 weeks after planting and the next three harvests were at 6-week intervals. Urea (100 kg N/ha) and KCl (60 kg K/ha) in solution were applied uniformly on 1-week-old grass for each harvest. Micronutrients in solution were applied on the soil surface of all treatments 10 days after the second and third harvests, at rates (soil basis) of 2.5 ppm for Cu, Mn, and Zn, 0.27 ppm for Mo, and 1 ppm for B. The sources were $CuSO_4 \cdot 5H_2O$, $MnSO_4 \cdot H_2O$, $ZnSO_4 \cdot 7H_2O$, $(NH_4)_6Mo_7 \cdot 4H_2O$, and H_3BO_3.

After the fourth harvest, the soil was air dried, screened, and replaced in the pot. The roots were washed thoroughly and finally rinsed with distilled water. The forage and roots were dried at 70C, weighed, and ground to pass a 20-mesh sieve in a stainless steel mill. The plant materials were analyzed for P, Ca, Mg, K, Cu, Zn, and Mn concentrations as above.

Fifty-gram soil samples were taken from each pot for the determination of organic P, inorganic P fractions, and total P. The methods of analysis were the same as above.

Experiment 2

The same soils used in Experiment 1 were planted with pigeon pea (*Cajanus cajan* L.) after an unsuccessful attempt to grow hairy indigo (*Indigofera hirsuta* L.) because of severe damage caused by red spider mites. Five seeds of pigeon pea, inoculated with a *Rhizobium* were sown in each pot on 8 June 1968. After 2 weeks, the plants were thinned to three/pot. Potassium chloride at the rate of 100 kg K/ha was applied uniformly on all treatments. The plants were cut 60 days after sowing. The tops and roots, and the analyses for Ca, Mg, P, Cu, Zn, and Mn were handled in the same manner as for pangolagrass.

Experiment 3

The same soils used in Experiments 1 and 2 were planted again to pangolagrass on 16 September 1968. The number of replications, however, was reduced to three because of soil losses incurred during screening. Urea (100 N kg/ha) and KCl (200 kg K/ha) in solution were applied uniformly on all treatments. The grass was cut 6 weeks after planting. Yield data and chemical analyses were handled in the same manner as above.

Optimum P Level x Lime Experiment

Lime was mixed with the pasture-surface soil at rates of 0 and 5 T/ha as $CaCO_3$. Two kilograms of soil were weighed into individual plastic bags, moistened to field capacity, and incubated under greenhouse conditions. Distilled water was added to the soil as necessary. At the end of a 41-day period, the soil was air-dried, thoroughly mixed with finely ground triple superphosphate at rates of 0, 150, 300, 450, 600, 750, and 900 kg P/ha, and placed in plastic pots. The experiment was a randomized complete block with four replications.

Three pangolagrass sprigs were planted in each pot on 12 June 1969. The grass was cut at the age of 6 weeks for the first and second harvests, 13 weeks for the third harvest, and 7 weeks for the fourth harvest.

Urea (100 kg N/ha) and KCl (100 kg K/ha) in solution were applied on all treatments 1 week after planting and 1 week after the first harvest. One hundred kilograms of N and 200 kg K/ha were applied uniformly after the second harvest, and finally, 200 kg N and 500 kg K/ha were applied 4 weeks after the third harvest.

In the fourth harvest, 20 ppm of Mn as $MnSO_4H_2O$ were sprayed on the grass at 3 weeks of age, in the first and second replications, while distilled water was sprayed on the other two replications. Spraying was repeated once during each of the next 2 weeks. The last spray was applied 2 weeks before harvest. The experiment was a split-plot design. The Mn treatment was the whole plot and P x Lime levels were subplots randomized within the whole plot with two replications.

One hundred grams of soil were taken from each pot immediately after the first and third harvests and dried at 70C. Inorganic P in the soil was fractionated as above. Plant tissue analysis was handled in the same manner as above.

$CaCO_3$-$MgCO_3$ x P Experiment

The pasture-surface soil was mixed with five lime materials of different $CaCO_3$ $MgCO_3$ ratio. Five T/ha of $CaCO_3$ were substituted with $MgCO_3$ on a chemical equivalent basis in the following percentages 0, 25, 50, 75, and 100. Two kilograms of the limed and unlimed soils were weighed into individual plastic bags, moistened to field capacity, and incubated under greenhouse conditions. Distilled water was added to the soil as necessary. At the end of a 40-day period, the soil was air-dried, thoroughly mixed with finely ground triple superphosphate at rates of 0 and 150 kg P/ha, and placed in plastic pots. The experiment was a randomized complete block with four replications.

Three pangolagrass sprigs were planted in each pot on 13 June 1968. Two harvests were cut at 6-week intervals. Urea (100 kg N/ha and KCl (100 kg K/ha) in solution were applied uniformly for both harvests, when the grass was 1-week old. Chemical analysis of plant material was the same as above.

Lime x Micronutrient Experiments

Experiment 1

Forty kilograms Mg/ha as $MgSO_4 \cdot 7H_2O$ and 150 kg P/ha as finely ground triple superphosphate were mixed with the pasture-surface soil. The soil was limed at the rate of 0, 5, and 10 T/ha as $CaCO_3$. Two kilograms of soil were treated with four levels of fritted micronutrient material[1] at rates of 0, 30, 60, and 90 kg/ha and placed in plastic pots. The experiment was a randomized complete block with four replications.

On 25 February 1968, one pangolagrass sprig was planted in each pot. Four harvests were cut at 6-week intervals. At each harvest, 100 kg/ha each of N as urea and K as KCl were applied uniformly on

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[1] FTE-503 with the following composition. Fe, 18.8%, Mn, 7.5%, Zn, 7.0%, Cu 3.0%, B, 3.0%, and Mo, 0.2%.

1-week-old grass. Manganese, Zn, and Cu concentrations in the plant tissue were determined as above.

Experiment 2

After removing the pangolagrass roots from the soil in the preceding experiment, the soil was air-dried and screened. All soils of the same lime treatment were thoroughly mixed. Two kilograms of soil were mixed with an experimental Mn chelate material[1] at rates of 0, 60, and 120 kg Mn/ha and replaced in plastic pots. The experiment was a complete randomized block with three replications.

Three pangolagrass sprigs were planted in each pot on 9 November 1968. After 3 weeks, 200 kg N/ha as urea and 500 kg K/ha as KCl were applied uniformly. The grass was cut when it was 11 weeks old. Manganese and Fe concentrations in the plant were determined as above.

Experiment 3

One week after the first forage harvest in the preceding experiment, $MnSO_4 \cdot H_2O$ in solution at rates of 0, 50, and 100 kg Mn/ha was added to the 0, 60, and 120 kg Mn/ha as Mn chelate treatments, respectively. Urea (100 kg N/ha) and KCl (250 kg K/ha) in solution were applied uniformly on all treatments. The grass was cut 7 weeks after the first harvest. Manganese and Fe concentrations in the plant tissue were determined as above.

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[1] Mn-NTA-2 (8.2% Mn) manufactured by Monsanto Co., St. Louis, Mo. The material was given by Dr. N. Gammon, Jr., Soils Department, Univ. Florida, Gainesville.

Silica-Organic Matter Experiment

Two kilograms of the pasture-surface soil were mixed with the following materials. Ca silicate and finely ground rice hulls (0.20% N, 0.05% P, 9.14% Si) to give rates of 0.47 and 1.41 T Si/ha, finely ground matured *Stylosanthes humilis* L. (1.32% N, 0.15% P, 0.07% Si) at rates of 5 and 10 T/ha, and dextrin at the rate of 10 T/ha. The treated soils and a control were placed in plastic pots and arranged in a completely randomized block design with each treatment replicated four times. Two sets were prepared consisting of these basic experimental units.

In the first set, hairy indigo seeds, inoculated with a *Rhizobium*, were sown, and in the second set, three pangolagrass sprigs per pot were planted on 2 March 1968. Twelve days after planting, urea (100 kg N/ha) and KCl (60 kg K/ha) in solution were applied uniformly for pangolagrass while only KCl was applied for hairy indigo. On 21 April 1968, the experiment with hairy indigo was discontinued because of severe damage caused by red spider mites.

Four pangolagrass harvests were cut at 6-week intervals. Nitrogen and K were applied in the same manner as above at rates of 100 kg/ha 10 days after the first, second, and third harvests. The plant material was dried and analyzed for P as above. Chemically available soil P was determined by the method of Bray and Kurtz described above.

RESULTS AND DISCUSSION

Characteristics of Climate and Soil of Los Diamantes Experiment Station

Climate

The Los Diamantes Experiment Station, where the soils were sampled, is on the northern slope of Mount Turrialba at an elevation of about 70 m above sea level. The area is humid as shown by the total rainfall of 4,441 mm/year and the amount of rainfall during the driest months (February, March, and April) which varies from 164 to 227 mm/month (Table 1). The average maximum and minimum temperatures are fairly even during the year and on the average do not become warmer than 31C and cooler than 19C.

Physical and Chemical Characteristics of the Soil

The Los Diamantes soil was formed from an alluvial deposit of volcanic material coming from the mountains (22). The data in Table 2 show that the soil texture was sandy loam. Results from the mineralogical analysis showed that the clay fractions were amorphous. There was not the slightest reflection in the X-ray diffraction curve to indicate the presence of crystalline mineral.

The total concentrations of some elements in the virgin and pasture soils are shown in Table 3. It is evident that Al was present in the soil in greatest amount. The four soils contained about the same amounts of the elements, except for Ca, Mg, and Zn which were present in higher concentrations in the pasture soil.

Table 1.--Rainfall and maximum and minimum temperatures at Los Diamantes Experiment Station.[1]

Month	Rainfall	Temperatures (C)	
		Maximum	Minimum
	mm	C	C
January	291	27	19
February	221	28	19
March	164	28	19
April	227	29	21
May	446	29	22
June	489	29	22
July	501	29	21
August	325	29	21
September	284	30	21
October	404	31	21
November	524	30	21
December	565	27	20
Total =	4,441	Avg. = 28	20

[1] Data are 15-year averages as reported by Blue *et al.* (24).

Table 2.--Particle size distribution and textural classification of Los Diamantes soils.

Soils	Sand	Silt	Clay	Textural Classification
		%		
Virgin surface	70.2	10.8	19.0	Sandy loam
Virgin subsoil	71.1	8.9	20.0	Sandy loam
Pasture surface	78.0	8.9	13.1	Sandy loam
Pasture subsoil	79.0	6.9	14.1	Sandy loam

Table 3.--Total concentration of elements in Los Diamantes soils.

Soils	Al	Fe	Ca	Mg	K	Na	Mn	Zn	Cu
	%						ppm		
Virgin surface	12.0	2.61	2.51	1.58	1.30	2.25	740	730	217
Virgin subsoil	11.9	2.98	3.00	1.73	1.30	2.25	733	430	200
Pasture surface	10.1	2.34	3.77	2.01	1.30	2.38	727	1,155	183
Pasture subsoil	11.3	2.73	3.28	1.84	1.30	2.28	733	980	200

Although the four soils had almost the same total amounts of Ca, Mg, K, and Na, the quantities of exchangeable cations differed greatly (Table 4). The pasture soils had much less exchangeable Ca and K than the virgin soils. Exchangeable Na was less in the pasture-surface soil than in the virgin-surface soil while Mg was less only in the pasture subsoil.

The organic matter content of the surface soils was relatively high (virgin 8.2% and pasture, 10.3%) and was twice that present in the subsoils (virgin, 3.6% and pasture, 5.2%). The total N in the soil followed the same trend as organic matter. The surface soils had an average of 0.44% N while the subsoils had 0.25% N. The soil pH varied from 5.8 to 6.1 in water suspension and 5.0 and 5.4 in 1 N KCl.

Soil P Fractions and Extractable Soil P

The data in Table 5 indicate that the soils of Los Diamantes had relatively large amounts of P. The soils, except the virgin subsoil, had total P contents greater than 2,000 ppm. In general, the organic form accounted for more P than any other; amounts varied from 37 to 50% of the total P. The surface soils had more organic P than the subsoils and the pasture soils more than the corresponding virgin soils. The amounts of organic P appeared to be correlated with the organic matter contents (Table 4).

The Al-P ranged from 7.2 to 13.2%, Fe-P, 6.4 to 10.9%, and Ca-P, 4.1 to 5.2% of the total P. Most of the inorganic P was occluded and represented 26.5 to 40.9% of total P. The subsoils contained greater proportions of their total P in the occluded form than the surface soils, as did the lvrgin soils when compared with the

Table 4.--Chemical properties of Los Diamantes soils.

Soils	Exchangeable cations				CEC	Organic Matter	Total N	pH	
	Ca	Mg	K	Na				H_2O	KCl
	---------- ppm ----------				meq/100 g	%	%		
Virgin surface	1,216	227	499	154	35	8.24	0.42	5.80	5.25
Virgin subsoil	763	138	320	62	34	3.62	0.20	5.90	5.00
Pasture surface	713	290	166	69	25	10.25	0.47	6.10	5.35
Pasture subsoil	417	66	260	94	24	5.19	0.29	5.90	5.40

Table 5.--Total P and distribution of P fractions in Los Diamantes soils.

Soils	Total P	Al-P	Fe-P	Ca-P	Organic P	Al-P	Fe-P	Ca-P	Organic P	Occluded P[1]
	ppm					% of total P				
Virgin surface	2,284	225	219	117	1,002	9.9	9.6	5.1	43.9	31.5
Virgin subsoil	1,761	126	192	72	649	7.2	10.9	4.1	36.9	40.9
Pasture surface	2,401	306	153	107	1,198	12.7	6.4	4.5	49.9	26.5
Pasture subsoil	2,012	266	143	104	865	13.2	7.1	5.2	43.0	31.5

[1] Calculated by subtracting from 100 the percentages of Al-P, Fe-P, Ca-P, and organic P.

corresponding pasture soils. The water-soluble P was less than 1 ppm in all soils and, therefore, it was disregarded.

The soil P, as measured with various chemical extractants, had a remarkably low availability (Table 6). The Florida and North Carolina methods extracted, in most cases, about 1 ppm; Truog, 6 to 15 ppm, and Bray-Kurtz, 10 to 29 ppm P. The Truog and Bray-Kurtz extractable P was twice as high in the virgin surface as in the pasture-surface soil. In general, the surface soils had more extractable P than the subsoils. The data in Tables 5 and 6 show that although the soils of Los Diamantes had large amounts of P, this P was present in forms not readily available for plant use.

Table 6.--Extractable P in Los Diamantes soils by various chemical methods.

Soils	Method			
	Truog	North Carolina	Bray and Kurtz	Florida
	ppm			
Virgin surface	15.0	1.9	29.0	1.1
Virgin subsoil	9.0	0.9	14.0	1.1
Pasture surface	9.0	0.7	14.0	1.3
Pasture subsoil	6.0	0.4	10.0	1.0

Laboratory Experiments

Results from the laboratory experiment are shown in Table 7. The amount of water-soluble P, in all cases, was negligible and, therefore, was not included in Table 7.

Table 7.--Effect of lime on P fractions, before and after P treatment[1], P retained, and pH of Los Diamantes soils.

Lime levels	Before P treatment			After P treatment			P retained	pH	
	Al-P	Fe-P	Ca-P	Al-P	Fe-P	Ca-P		H_2O	KCl
(T/ha)	ppm						ppm		
				Virgin surface					
0	274 a[2]	194 ab	132 a	981 a	344 a	137 a	1.008 a	5.20	4.80
3.56	299 b	202 bc	122 b	1.004 a	367 a	137 a	988 a	5.60	5.20
7.12	299 b	217 cd	136 a	997 a	351 a	139 a	998 a	6.15	5.80
10.68	281 a	212 d	126 b	1.096 b	373 b	140 a	1,178 b	6.50	6.15
				Virgin subsoil					
0	169 a	175 a	80 a	839 a	366 a	92 a	1.051 a	5.80	4.80
3.56	168 a	171 a	81 a	926 b	386 b	86 b	1.137 b	5.50	5.20
7.12	171 a	176 a	78 a	955 b	401 c	103 c	1.243 c	6.50	5.95
10.68	170 a	177 a	86 b	968 b	407 c	113 d	1.259 c	6.90	6.35
				Pasture surface					
0	334 a	149 a	144 a	1.452 a	322 a	139 a	1,400 a	5.00	4.70
3.56	318 a	125 b	146 a	1.433 a	320 a	141 a	1.402 a	5.40	5.10
7.12	321 a	126 b	142 a	1.361 a	311 a	139 a	1.382 a	5.80	5.60
10.68	328 a	132 b	145 a	1.364 a	317 a	142 a	1.415 a	6.15	5.90

Table 7.--Continued

	Before P treatment			After P treatment				pH	
Lime levels	Al-P	Fe-P	Ca-P	Al-P	Fe-P	Ca-P	P retained	H_2O	KCl
(T/ha)	ppm						ppm		
				Pasture subsoil					
0	325 a	104 a	165 a	1,437 a	339 a	161 a	1,354 a	5.90	5.40
3.56	315 a	97 a	162 a	1,445 a	343 a	161 a	1,499 b	6.15	5.70
7.12	315 a	110 a	158 a	1,597 b	353 ab	169 ab	1,641 c	6.60	6.10
10.68	289 a	98 a	175 b	1,592 b	372 b	176 b	1,715 c	6.90	6.40

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[1] Phosphorus treatment was 1 g of soil in 50 ml of 50 ppm P solution.

[2] Values followed by the same lower case letter within respective column of each soil are not significantly different at 0.05 probability level.

The soil pH, 6 weeks after incubation (Table 7), was lower than before the preincubation period (Table 4) especially in the surface soils. This decrease in pH could have been caused by acids produced during nitrification and organic matter decomposition. The postincubation soil pH (water suspension) increased with lime rates from pH 5.0 (unlimed) to pH 6.9 (10.68 T $CaCO_3$/ha).

Liming the soils did not change significantly the quantities of Al-P except in the virgin-surface soil, in which case, Al-P increased with lime rates through 7.12 T $CaCO_3$/ha (Table 7). Iron P was significantly affected by lime only in the surface soils. The effect of lime, however, differed in the two surface soils. Iron P increased with lime rates in the virgin-surface soil while a decrease occurred in the pasture-surface soil. The Ca-P content of the subsoils was significantly increased by lime application only at the highest lime rate. The magnitude of increase, however, was not large, an average of 8 ppm P over the control.

The soils of Los Diamantes had high capacities to retain P from the KH_2PO_4 solution as indicated by the data in Table 7. The amounts of P retained varied from 988 to 1,715 ppm. The pasture soils retained more P than the virgin soils. Lime increased the capacity of the soils to retain P except for the pasture-surface soil. The effect of lime on the P retention capacity was more pronounced in the subsoils than in the surface soils. Most of the P retained by the soils was in the form of Al-P and a lesser amount as Fe-P. After P treatment, Al-P increased three- to four-fold, Fe-P increased two- to three-fold, and Ca-P increased slightly only in the virgin subsoil.

In the pasture-surface soil, lime did not influence the amount of Al-P and Fe-P formed during P treatment, and only at the highest lime rate did the Al-P and Fe-P of the virgin-surface soil increase significantly. Moreover, lime did not increase the amount of Ca-P formed in the two surface soils during P treatment. The data in Table 7 show that lime had its greatest effect on the subsoil in increasing the formation of Al-P, Fe-P, and Ca-P during P treatment. This suggests that Al, Fe, and possibly Ca exist in the subsoils in different forms than those present in the surface soils. Probably in the surface soils which had a high organic matter content, Al, Fe, and Ca were part of metal-organic matter complexes which did not become reactive in P retention with increase in soil pH.

The effect of lime on the amounts of Al extracted by various chemical solutions from the soils is shown in Table 8. The amounts of Al varied with the chemical extractant used in the following order: 0.1 N HCl> >1.0 N NH_4OAc (pH 4.8)> >1.0 N KCl. The amount of exchangeable Al was small and possibly had a negligible effect on P retention. Amounts of exchangeable Al in the unlimed soils were 1.42 to 8.70 ppm; 1.0 N NH_4OAc (pH 4.8)-extractable, 122 to 441 ppm, and 0.1 N HCl-extractable, 1,823 to 3,790 ppm. The exchangeable Al, in most cases, was not measurable after lime was applied. The amount of 1.0 N NH_4OAc (pH 4.8)-extractable Al decreased markedly with increasing lime rates but lime rates did not have a significant effect on the 0.1 N HCl-extractable Al. The 0.1 N HCl-extractable Al was found by Yuan (195) to be highly correlated with the capacity of some Florida soils for P sorption. He speculated that 0.1 N HCl-extractable Al may have come from amorphous weathered products containing Al. The large amount of 0.1 N HCl-extractable Al can probably be attributed to the amorphous nature of the inorganic soil colloids.

Table 8.--Effect of lime on the Al extracted from Los Diamantes soils by three chemical solutions.

Lime levels	1.0 N KCl	1.0 N NH_4OAc, pH 4.8	0.1 N HCl	1.0 N KCl	1.0 N NH_4OAc, pH 4.8	0.1 N HCl
(T/ha)		ppm			ppm	
		Virgin surface			Pasture surface	
0	1.95 a[1]	122 a	2,145 a	8.70 a	304 a	3,790 a
3.56	0.11 b	82 b	2,070 a	1.87 b	216 b	3,632 a
7.12	0 b	61 c	1,836 a	0 c	160 c	3,592 a
10.68	0 b	53 c	1,875 a	0 c	144 c	3,360 a
		Virgin subsoil			Pasture subsoil	
0	3.65 a	202 a	1,823 a	1.42 a	411 a	2,894 a
3.56	0 b	146 b	2,013 a	0.79 b	353 a	2,899 a
7.12	0 b	107 c	1,822 a	0.32 b	306 b	3,152 a
10.68	0 b	93 c	2,079 a	0.43 b	292 b	3,184 a

[1] Values followed by the same letter within respective column of each soil are not significantly different at 0.05 probability level.

Fig. 1 shows that the Al extracted with 1.0 N NH_4OAc (pH 4.8) and 0.1 N HCl was significantly correlated with the P retained by the Los Diamantes soils. The larger amount of extractable Al in the pasture soils would explain their higher P retention capacity as compared with the virgin soils.

Greenhouse Experiments

Results from greenhouse experiments, with two or more harvests of pangolagrass, are discussed in terms of the total oven-dry forage yields. However, comparisons between harvests are discussed where it is appropriate to show differences in yield response to treatments. Summary data are presented in this section while supplementary data are included in the appendix.

Soil x Lime x P Experiments

Experiment I

Forage yields.--The data in Tables 9 and 10 show that, on the average, the surface soils produced more forage than the subsoils (see also Fig. 2, A and B). The virgin soils gave higher forage yields than the pasture soils, however, the difference was significant only when corresponding subsoils were compared. The presence of more available plant nutrients in the virgin soils (Tables 4 and 6) must have favored better plant growth.

When P was not applied, the yields obtained from the subsoils were low compared with the surface soils. The total oven-dry forage yields of four pangolagrass harvests in the unlimed, P_0 treatment were as follows: virgin surface, 28.29, virgin subsoil, 0.98, pasture surface, 20.90, and pasture subsoil, 1.22 g/pot. The application of P in the

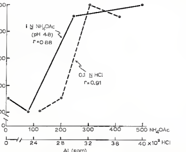

Fig. 1.--Relationship of 1.0 N NH$_4$OAc (pH 4.8)- and 0.1 N HCl-extractable Al with P retention in Los Diamantes soils.

Table 9.--Effect of lime and P levels on total pangolagrass forage yields from four harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
		g/pot			
0	0	28.29 b[1]	0.98 a	20.90 bcd	1.22 a
	50	31.90 b	15.92 c	27.50 cde	1.32 a
	100	46.63 c	29.91 d	28.74 de	22.17 bc
	150	45.22 c	40.50 d	40.09 f	22.94 c
	Avg.	38.01 m	21.83 k	29.31 l	14.89 lj
5	0	7.66 a	1.48 a	14.42 b	0.29 a
	50	32.19 b	13.99 bc	21.08 bcd	2.72 a
	100	29.30 b	21.87 cd	29.84 def	19.14 bc
	150	34.16 b	24.51 cd	34.12 af	14.58 bc
	Avg.	25.83 kl	15.46 j	24.86 kl	9.18 hl
10	0	5.36 a	3.36 ab	2.37 a	0.59 a
	50	8.92 a	4.18 ab	13.99 b	4.65 ab
	100	15.11 ab	20.10 cd	22.38 bcd	11.42 ab
	150	28.11 b	21.15 cd	17.34 bc	4.84 ab[2]
	Avg.	14.38 l	12.20 l	14.50 l	5.37 h
Soil Avg.		26.07 x	16.50 [illegible]	22.59 x	9.82 z

[1] Values followed by the same lower case letter within respective column of the letter group a-f and within the lettered groups l-m and x-z are not significantly different at 0.05 probability level.

[2] Insect damaged.

Table 10.--Analysis of variance for forage yield data in Table 9.

Source	df	MS	F
Rep	3	73.4	1.7
Soil	3	2,464.4	56.6**
Lime	2	3,387.0	77.8**
Phosphorus	3	3,979.4	91.4**
S x L	6	202.1	4.6**
S x P	9	93.2	2.1*
L x P	6	79.2	1.2
S x L x P	18	238.4	5.5*
Error	141	43.5	
Total	191		

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

subsoils resulted in increased plant growth as shown in Figs. 2, B. The yields produced, in some instances, were almost comparable with the yields of the surface soil, particularly in the virgin soil. This indicated that P in the subsoils was unavailable, and consequently, limited plant growth occurred when P was not added to the soil. Blue (23) speculated that available P was more plentiful in the subsoil than the surface soil from Los Diamantes, and after the plant was established, sufficient P was obtained from the subsoil to preclude response to surface applied P. Results from this study, however, showed that this was not the case.

Tables 9 and 10 show that all treatment effects and their interactions, except the lime x P interaction, were significant. The nonsignificant lime x P interaction indicated that lime and applied P were independent of each other in their influence on plant growth. The relationship of total oven-dry forage with lime and P levels averaged for all soils is shown in Fig. 3. For all lime levels, there

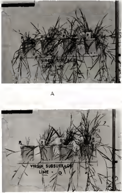

Fig. 2.--Effect of fertilizer P on the growth of pangolagrass in unlimed virgin (A) surface and (B) subsurface soils.(Phosphorus treatments P_0, P_1, P_2, and P_3 were 0, 50, 100, and 150 kg/ha, respectively).

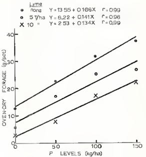

Fig. 3.—Effect of lime and P levels on total forage yields from four pangolagrass harvests.

was a linear increase of forage production with increased levels of applied P. The yield responses to applied P were almost equal. Yield response to P decreased slightly with increased lime levels as indicated by the following regression coefficients: unlimed, 0.166, 5 T lime/ha, 0.141, and 10 T lime/ha, 0.134. Regression coefficients for the 0 and 10 T lime/ha levels were significant at 0.01 probability level and for the 5 T lime/ha at 0.05 probability level.

Insect damage was severe in some treatments, particularly in the P_3, 10 T lime/ha treatment as indicated in Table 9. The data from this treatment, therefore, were not included in the calculations for the 10 T lime/ha regression line.

The highest P treatment in this experiment was comparable to the broadcast rate (172 kg P/ha) application of Blue (24). Whereas Blue failed to obtain significant forage yield responses from broadcast applied P in Los Diamantes soils, highly significant increases in yields were obtained from the P treated soils in this study (Fig. 3). In the broadcast application, most of the fertilizer P was possibly retained in the surface soil and very little leached into the root zone even under heavy rainfall conditions in Los Diamantes. It was shown earlier that the soils of Los Diamantes have high P retention capacity. In addition, newly planted grasses would not have the necessary root mass to intercept effectively any leached P from the soil surface. Mixing finely ground triple superphosphate with the soil, as was the case in this study, must have provided better root and P contact, hence, forage yield responses were obtained. Whether established pasture grasses will respond to P broadcast on the Los Diamantes soils at the same P levels as used in this study awaits further investigation. Blue did obtain response to both surface and subsurface banded P in the establishment of pangola and elephant grasses. However, the effective P concentration was estimated to be approximately 516 kg P/ha. With this high concentration, P fixation and the root mass would be of less importance in P nutrition than where P was broadcast applied.

It was observed that with time, forage growth in the surface soils improved markedly, as yields from the fourth harvest for the P_0 and P_1 treatments were about the same (see appendix, Table 59). Fixation of applied P in the soil generally increases with time, which probably accounted for part of this lack of yield difference. However, this suggested that as the grass developed a good root system and became well established, it was eventually capable of absorbing native soil P from the surface soils. It is evident from the data (Tables 9 and 10, and Fig. 3) that forage yields were higher from the unlimed soil than from the limed soils. Forage yields decreased with increased lime rates. Fig. 4, A and B illustrate further the depressing effect of lime on plant growth.

Root weights.--Tables 11 and 12 show that there were no treatment interaction effects on root weights. For the P_0 treatment, the grass developed larger root system when planted in the surface soils than in the subsoils. Root development was greatly enhanced by fertilizer P application. The average root weights increased linearly with increased P levels. The effect of applied P on root development was most significant in the subsoils. Root weights in the subsoils were increased from less than 1 g/pot (P_0 treatment) to as high as 7.34 g/pot (P_3 treatment). In particular, roots obtained from the virgin subsoil, at the higher P treatments, were even larger than those produced in the virgin-surface soil. This would explain why the total forage yield

A

B

Fig. 4.--Effect of lime on the growth of pangolagrass in (A) pasture (cult.) surface and (B) virgin subsoil (subsurface). (Lime was applied at rates 0, 5, and 10 T/ha in the 0, 1, and 2 lime levels, respectively. P_0 was no P applied, and P_3 was 150 kg P/ha).

Table 11.--Effect of P levels on pangolagrass root weights after four forage harvests.

Soils	P levels (kg/ha) 0	50	100	150	Avg.
	----------------	----------------	g/pot	----------------	----------------
Virgin surface	2.42	3.92	4.93	6.01	4.32 a[1]
Virgin subsoil	0.98	3.79	6.29	7.34	4.60 ab
Pasture surface	3.23	4.23	6.00	8.88	5.59 b
Pasture subsoil	0.53	2.88	5.03	5.99	3.61 a
Avg.	1.78 w	3.71 x	5.56 y	7.05 z	4.53

[1] Values followed by the same lower case letter within the lettered groups a-b and w-z are not significantly different at 0.05 probability level.

Table 12.--Analysis of variance for pangolagrass root data in Table 11.

Source	df	MS	F
Rep	3	27.84	3.86**
Soil	3	32.23	4.46**
Lime	2	210.62	29.17**
Phosphorus	3	250.08	34.64**
S x L	6	12.22	1.69
S x P	9	6.27	0.87
L x P	6	10.16	1.41
S x L x P	18	9.69	1.34
Error	141	7.22	
Total	191		

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

of the virgin subsoil approached that of the virgin-surface soil as P levels were increased.

Lime was detrimental to root growth as it was to forage production. Root weights decreased with increased lime rates. The effects of lime levels on root and forage production were parallel (Fig. 5). In the surface soils, increasing the lime level from 0 to 10 T/ha decreased root weights from almost 6 to less than 1 g/pot when P was omitted (Table 13). The highest P level was needed to enable the grass from the 10 T lime/ha treatment to produce the same root mass as the grass from the unlimed, P_0 treatment.

The data in Table 11 emphasize the importance of adequate P supply in the soil when newly cleared lands are planted to crops. The surface organic debris and the mineral soil are mixed during clearing and leveling operations resulting in the dilution and fixation of available P originally present at the interface of the organic debris and mineral soil. When crop production is desired immediately after clearing, P fertilization becomes necessary for plant root development.

Aside from the unfavorable effects of N and P immobilization on plant growth during organic matter decay, organic acids and gases are produced and they may reach concentrations that are toxic to normal root development (146). Concentrations of organic acids and gases could easily attain toxic levels in newly cleared, wet, tropical virgin lands of Costa Rica because of the large quantity of organic debris from the rainforest incorporated into the soil. This would explain why Blue et al. (24) encountered considerable difficulty in establishing pangolagrass pastures on newly cleared lands of Los Diamantes, Costa Rica. The plants were stunted in growth and no visible plant development occurred for several months, after which growth proceeded at a

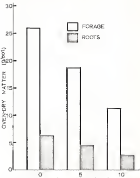

Fig. 5.--Effect of lime on total pangolagrass forage yields from four harvests and root weights.

Table 13.--Effect of lime and P levels on pangolagrass root weights after four forage harvests.[1]

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
		g/pot			
0	0	4.48[2]	0.83	5.70	0.93
	50	4.85	5.50	5.60	5.75
	100	7.18	7.38	7.23	6.98
	150	9.33	7.63	14.60	7.63
	Avg.	6.46	5.33	8.28	5.32
5	0	1.70	0.70	3.18	0.35
	50	5.15	4.15	4.18	1.63
	100	5.80	6.85	7.33	5.58
	150	4.22	5.98	7.55	8.00
	Avg.	4.22	4.42	5.56	3.89
10	0	1.08	1.40	0.83	0.33
	50	1.75	1.73	2.93	1.28
	100	1.80	4.65	3.48	2.55
	150	4.48	8.43	4.48	2.35
	Avg.	2.28	4.05	2.93	1.63

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[1] Approximately 7 months after the pangolagrass was planted.

[2] Average of four replications.

normal rate. The first harvest was made 5 to 6 months after planting. In this study, no difficulty was encountered in establishing pangolagrass on Los Diamantes soils except for the subsoil, P_0 treatments. It may be advisable to delay the utilization of newly cleared lands for crop production to allow organic matter decomposition, thus ensuring among other factors, better P availability.

Soil pH.--The average pH values of the limed soils were within the range generally considered optimum for plant growth (Table 14). Soil pH was increased by P and lime applications. The unlimed soils had pH values that varied from 5.10 to 5.62 while the pH of the limed soils ranged from 5.65 to 6.59.

Table 14.--Effect of lime and P levels on the pH of Los Diamantes soils.

Lime levels (T/ha)	P levels (kg/ha) 0	50	100	150	Avg.
0	5.10[1]	5.28	5.55	5.62	5.39
5	5.65	5.97	6.14	6.21	5.99
10	6.30	6.40	6.56	6.59	6.46
Avg.	5.68	5.88	6.08	6.14	5.95

[1] Average of four soils and four replications.

Phosphorus concentrations.--The P concentrations in pangolagrass forage and root mass were significantly higher from the surface soils than from the subsoils (Table 15). Forage from the virgin-surface soil had a significantly higher P concentration than that from the pasture-surface soil. In the P_0 treatment, the percentages of P in forage

Table 15.--Average P concentrations in pangolagrass forage and root as affected by P levels.

Soils	P levels (kg/ha) 0	50	100	150	Avg.
	----------------------	%	----------------------		
		Forage			
Virgin surface	0.08[1]	0.09	0.10	0.10	0.09 a
Virgin subsoil	0.04	0.06	0.07	0.08	0.06 b
Pasture surface	0.06	0.07	0.09	0.08	0.08 c
Pasture subsoil	0.04	0.05	0.06	0.07	0.06 b
Avg.	0.05 x[2]	0.07 y	0.08 z	0.08 z	0.07
		Root			
Virgin surface	0.05	0.05	0.06	0.06	0.05 d
Virgin subsoil	0.04	0.04	0.05	0.05	0.04 e
Pasture surface	0.05	0.06	0.07	0.06	0.06 f
Pasture subsoil	0.03	0.04	0.04	0.04	0.04 e
Avg.	0.04 g	0.04 g	0.05 h	0.05 h	0.05

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[1] Average of four harvests.

[2] Values followed by the same letter within the lettered groups a-c, d-f, g-h, and x-z are not significantly different at 0.05 probability level.

from the virgin-and pasture-surface soils were 0.08 and 0.06, respectively, while forage from the subsoils had 0.04% P. The roots had lower P concentrations than the forage. Roots from the P_0. surface soil treatments contained 0.05% P while those from the virgin and pasture subsoils contained 0.04 and 0.03% P.

Although P fertilization increased significantly the forage P concentrations, those in the fertilized plants were surprisingly low. The highest average P concentration was 0.10% P in the virgin-surface soil at the P_3 treatment. The P concentrations of forages from the subsoils were affected more by P fertilization than were forages from surface soils. The P concentrations in forages from the subsoils, at the highest P level, were about 0.08% which was twice that present in the control. In contrast to the forage, P concentrations in the roots were less affected by P fertilization. In general, root P concentrations increased with P levels, only by 0.01% P over the P_0 treatment. Lime did not affect the P concentrations of either the forage or roots.

Tables 16 and 17 show the effects of lime and P levels on the total P contents of roots and four forage harvests. The total P contents of forage from the surface soils were significantly higher than those from the subsoils. Forages from the virgin soils had higher total P contents than those from the corresponding pasture soils (Table 16). The total P contents of forage and root masses decreased significantly with higher lime applications.

Phosphorus absorbed by the forage and root masses from the subsoils (P_0 treatment) was remarkably low as compared with the surface soils. Total forage P contents from the P_0 treatment were virgin surface, 10.2, virgin subsoil, 1.6, pasture surface, 8.8, and pasture subsoil, 0.3 mg/pot. The root P contents varied from 0.2 to 1.9 mg/pot.

Table 16.--Effect of lime levels on the total P contents of four pangolagrass forage harvests and roots.

	Lime levels (T/ha)			
Soils	0	5	10	Avg.
	mg/pot			
		Forage		
Virgin surface	33.1 e[1]	22.0 d	13.9 c	22.3 f
Virgin subsoil	14.0 c	11.8 bc	9.3 bc	11.7 g
Pasture surface	21.5 d	19.5 d	11.5 bc	17.5 h
Pasture subsoil	9.7 b	6.5 ab	3.9 a	6.5 i
Avg.	25.9 j	19.9 k	12.9 l	14.7
		Root		
Virgin surface	3.9 p	2.2 no	1.4 mn	2.5 u
Virgin subsoil	2.1 mno	1.9 mno	2.3 no	2.1 tu
Pasture surface	6.2 q	3.3 op	1.5 mn	3.7 v
Pasture subsoil	2.1 mno	1.7 mno	0.7 m	1.5 t
Avg.	3.6 r	2.3 s	1.5 s	2.4

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[1] Values followed by the same lower case letter within the lettered groups a-e, f-i, j-l, m-q, r-s, and t-v are not significantly different at 0.05 probability level.

Table 17.--Effect of P levels on the total P contents of four pangolagrass forage harvests and roots.

	P levels (kg/ha)			
Soils	0	50	100	150
	mg/pot			
	Forage			
Virgin surface	10.2 bcd[1]	20.3 ef	27.9 gh	33.6 h
Virgin subsoil	1.6 a	7.1 abc	17.0 def	21.2 ef
Pasture surface	8.8 bc	16.1 de	22.8 fg	22.3 efg
Pasture subsoil	0.3 a	4.1 ab	11.8 cd	9.7 bc
P Avg.	5.2 i	11.9 j	19.9 k	21.7 l
	Root			
Virgin surface	1.1 mno	1.9 mnopqr	3.1 pqrs	3.8 rs
Virgin subsoil	0.5 mn	1.4 mnop	3.0 oqrs	3.6 qs
Pasture surface	1.8 mnopq	2.1 mnopqr	4.1 s	6.7 t
Pasture subsoil	0.2 m	1.3 mnop	2.1 mnopqr	2.4 nopqrs
P Avg.	0.9 u	1.7 u	3.1 v	4.1 w

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[1] Values followed by the same lower case letter within the lettered groups a-h, i-l, m-t, and u-w are not significantly different at 0.05 probability level.

Phosphorus absorbed by both forage and root masses increased significantly with increase in P levels (Table 17). The grass responded to P fertilization differently in the virgin and pasture soils. Whereas forage P uptake consistently increased with P levels in the virgin soils, P uptake tended to level off at higher P levels in the pasture soils. This was probably because of higher yields and less P fixation in the virgin soils.

The marked increases in P uptake by forage with P fertilization were mainly due to higher dry matter production because plant P concentrations did not increase appreciably. Although P from the fertilizer was readily available when applied in the soils as indicated by the forage yields, apparently the rate of availability was not high enough to give high forage P concentrations. The P concentrations obtained in this experiment were below the concentration (0.15% P) considered adequate for grazing animals (78).

Phosphorus recovery.--Percent P recoveries by the four pangolagrass forage harvests were calculated by subtracting the forage P content of the P_0 treatment from the P contents of treated plants and dividing the differences by the amounts of P applied. Although this method is not as accurate as the use of ^{32}P, it does provide some estimate regarding the efficiency of fertilizer use in soils. This discussion is limited to the unlimed soils where soil conditions were considered best for plant growth.

Fertilizer P recovery was higher from the virgin soils than from the pasture soils (Table 18). Phosphorus recovery varied from 7.1 to 24.4% of the applied P. With the exception of the pasture subsoil, the percentage of applied P recovered increased with increased rates of applied P. The percent of applied P recovered was higher in the virgin soils than in the pasture soils possibly because of lower P fixation in the virgin soils. The data in Table 17 indicated that in the pasture land, low rates of P applied in the subsoil were more efficient than when applied in the surface soils. Low rates of P were more efficient in the virgin land, however, when applied in the surface soil.

Table 18.--Effect of P levels on fertilizer P recovery by four pangolagrass forage harvests.

P levels	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
(kg/ha)	%			
0	-	-	-	-
50	13.3	12.7	7.1	11.5
100	18.8	13.8	7.5	10.2
150	17.2	24.4	11.9	11.4

Calcium and Mg concentrations.--Calcium and Mg concentrations in the forage were higher in the fourth than in the first harvest. Since the trend of results, as shown in Table 67 of the appendix, was similar for the first and fourth harvests, the average of these two harvests is presented for the discussion (Table 19).

Lime increased the Ca and Mg concentrations in the forage. Calcium and Mg concentrations in forage from the unlimed surface soils increased with P levels. Better plant growth with P fertilization must have increased the demand of the plants for Ca and Mg. In addition, Ca was present in the triple superphosphate fertilizer. Calcium and Mg concentrations in forage from the unlimed virgin-surface soil were higher than from the unlimed pasture surface soil. The differences were reversed by liming, particularly the Ca concentrations.

Table 19.--Calcium and Mg concentrations in pangolagrass forage as affected by lime and P levels.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface		Virgin subsoil		Pasture surface		Pasture subsoil	
		Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg
		%							
0	0	0.38[1]	0.40	0.96	0.46	0.31	0.37	0.69	0.40
	50	0.40	0.45	0.39	0.28	0.36	0.47	0.42	0.31
	100	0.39	0.50	0.30	0.24	0.39	0.47	0.39	0.32
	150	0.47	0.52	0.33	0.30	0.37	0.43	0.43	0.37
	Avg.	0.41	0.47	0.50	0.32	0.36	0.44	0.48	0.35
5	0	0.58	0.44	1.37	0.48	0.34	0.44	1.23	0.41
	50	0.46	0.47	0.64	0.43	0.50	0.52	0.84	0.43
	100	0.41	0.52	0.53	0.43	0.50	0.47	0.51	0.35
	150	0.41	0.50	0.45	0.40	0.59	0.47	0.57	0.36
	Avg.	0.47	0.48	0.75	0.44	0.48	0.48	0.79	0.39
10	0	0.61	0.53	1.47	0.46	0.79	0.46	1.84	0.32
	50	0.54	0.44	0.83	0.46	0.69	0.53	1.23	0.41
	100	0.46	0.45	0.98	0.49	0.57	0.49	0.79	0.39
	150	0.52	0.48	0.77	0.45	0.64	0.49	0.85	0.39
	Avg.	0.53	0.48	1.01	0.47	0.67	0.49	1.18	0.38

[1] Average of first and fourth harvests.

In the limed surface soils, generally, the forage had higher Ca concentrations when P was not added to the soils. Likewise, in the subsoils, forage Ca concentrations were high from the P_0 treatment. Calcium concentrations decreased with increased P levels probably because of the dilution effect of larger dry matter production. Forage Mg concentrations seemed to be much less affected by lime and forage yields.

Lime increased the Ca concentrations of the roots from the subsoils, whereas either no effect or a decrease in Ca concentrations occurred in the surface soils (Table 20). Magnesium concentrations in the roots did not change markedly with lime applications, except in one case. Roots from the surface soils had higher Ca and Mg concentrations than roots from the subsoils, and roots from the virgin soils had higher Ca and Mg concentrations than those from the pasture soils.

Potassium concentrations.--Pangolagrass forage had relatively high K concentrations (Table 21). Potassium concentrations in the first forage harvest were not changed appreciably by liming the soils, except for the pasture surface soil, in which case, the forage K concentration from the 10 T lime/ha level was higher by 1.03% than that from the unlimed soil. Forage K concentrations in the first harvest were generally higher in the virgin soils than in the pasture soils.

Forage K concentrations decreased markedly with the number of forage harvests especially in the unlimed soils. In the third and fourth harvests, K concentrations increased with lime levels. An appreciable decrease in K concentration, however, occurred as early as the second harvest.

Table 20.--Effect of lime on the Ca and Mg concentrations in pangolagrass roots.

Soils	Lime levels (T/ha) 0	5	10	Avg.
	----------	----------	%	----------
			Ca	
Virgin surface	0.98	1.05	0.96	1.00
Virgin subsoil	0.38	0.50	0.65	0.51
Pasture surface	1.26	0.89	0.99	0.99
Pasture subsoil	0.35	0.45	0.66	0.49
Avg.	0.75	0.73	0.77	0.75
			Mg	
Virgin surface	0.29	0.32	0.29	0.30
Virgin subsoil	0.20	0.21	0.28	0.23
Pasture surface	0.44	0.30	0.25	0.33
Pasture subsoil	0.20	0.18	0.19	0.19
Avg.	0.29	0.25	0.25	0.26

Table 21.--Effect of lime levels on the K concentrations in four pangolagrass forage harvests.[1]

Lime	Harvests							
T/ha	1	2	3	4	1	2	3	4
	%							
	Virgin surface				Pasture surface			
0	2.99[2]	2.71	1.85	0.88	2.22	1.56	0.83	0.89
5	2.97	2.61	2.50	2.13	2.52	1.74	1.42	1.28
10	2.98	2.65	2.45	2.57	3.25	2.69	2.27	2.27
Avg.	2.98	2.66	2.27	1.90	2.66	3.00	1.51	1.48
	Virgin subsoil				Pasture subsoil			
0	2.86	2.19	1.52	1.62	2.60	2.12	1.79	1.90
5	2.52	2.55	1.94	2.40	2.81	2.33	1.76	1.51
10	2.81	2.43	2.11	1.98	2.70	2.23	1.97	2.54
Avg.	2.73	2.39	1.86	2.00	2.70	2.23	1.84	1.98

[1] 150 kg P/ha applied.

[2] Average of four replications.

Forage K concentrations from the unlimed virgin-surface soil, P_0 treatment, did not change appreciably for the four harvests (Fig. 6). There was a slight increase in K concentration in the first harvest for the P_1, P_2, and P_3 treatments over the control. No change in K concentrations occurred with increased P levels in the second harvest, however, these concentrations were lower than those in the first harvest. In the third and fourth harvests, K concentrations decreased with increased P levels. At the P_3 treatment, forage K concentration decreased from 3% in the first harvest to 1% in the fourth, which was the largest decrease.

In contrast to the virgin-surface soil, K concentrations in forage from the unlimed pasture-surface soil, P_0 treatment, decreased appreciably with the number of harvests (Fig. 7). Furthermore, a decrease in K concentration occurred in the first harvest at the P_3 treatment after an initial increase at the lower P levels. In the second, third, and fourth harvests, K concentrations decreased with increased P levels. Forage K concentrations from the unlimed subsoils were similarly affected by P applications but to a lesser extent (Figs. 6 and 7).

Although K was added to the soil for each harvest, the amount added (75 mg K/pot) apparently was not sufficient to meet the requirement of the grass (Table 22) except for the subsoil, P_0 treatments (see appendix, Table 68). Forage K content in the first harvest from the surface soils with a 150 kg P/ha application was two to three times the amount of K applied. In the unlimed virgin-surface soil, 357 mg of soil K/pot were absorbed by the forage before any significant

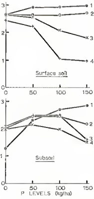

Fig. 6---Forage K concentrations in four pangolagrass harvests as affected by P levels in unlimed virgin soil. (Numbers 1, 2, 3, and 4 refer to 1st, 2nd, 3rd, and 4th harvest, respectively).

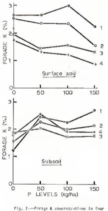

Fig. 7.--Forage K concentrations in four pangolagrass harvests as affected by P levels in unlimed pasture soils. (Numbers 1, 2, 3, and 4 refer to 1st, 2nd, 3rd, and 4th harvest, respectively).

Table 22.--Effect of lime levels on the K contents of four pangolagrass forage harvests.[1]

Lime levels	Harvests							
	1	2	3	4	1	2	3	4
T/ha	mg/pot							
	Virgin surface				Pasture surface			
0	218[2]	266	231	121	290	136	68	87
5	141	282	236	222	213	164	121	80
10	39	231	201	348	39	129	120	131
Avg.	133	260	223	181	181	143	103	99
	Virgin subsoil				Pasture subsoil			
0	314	188	172	142	149	132	96	86
5	82	105	186	162	44	64	68	92
10	32	100	146	164	15	28	21	57
Avg.	143	131	168	156	69	75	62	78

[1] 150 kg P/ha applied.

[2] Average of four replications.

decrease in K concentration occurred.[1] The forage absorbed 490 mg of soil K/pot from the unlimed virgin-surface soil and 269 mg/pot from the unlimed pasture-surface soil before the forage K concentrations decreased to less than 1%. The low amount of exchangeable K (Table 4) in the pasture-surface soil probably explains the lower capacity of the pasture-surface soil to maintain forage K concentrations as high as the virgin-surface soil.

Forage yields for the first three harvests, averaged for all soils and lime levels, increased linearly with P levels (Fig. 8). In the fourth harvest, however, a decline in forage yield occurred at the P_3 treatment. This decline could have been due to the depletion of available K in the soil by the previous harvests. According to Gammon and Blue (74), pangolagrass should have at least 2% K for optimum growth. The K concentrations in the third and fourth harvests were, in most cases, below the optimum K level especially with forages from the P_3 treatment.

Micronutrient concentrations.--In the unlimed soils, pangolagrass forage contained much higher concentrations of Mn than Zn and Cu (Table 23). Forage Mn concentrations in the unlimed soils were generally five and eight times as high as the concentrations of Zn and Cu, respectively. Manganese concentrations were decreased to very low values by liming the soils, whereas there was either no change (surface soils) or an increase (subsoils) in the concentrations of Zn and Cu. For instance, Mn concentrations in the forage from the virgin-surface

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[1] Soil K absorbed by the forage was calculated by subtracting the amount of K applied in the soil from the forage K content.

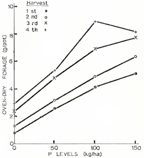

Fig. 8.--Forage yields from four pangolagrass harvests as affected by P levels.

Table 23.--Effect of lime on micronutrient concentrations in pangolagrass forage.[1]

Lime levels (T/ha)	Micronutrients					
	Mn	Zn	Cu	Mn	Zn	Cu
	ppm					
	Virgin surface			Pasture surface		
0	227[2] f[3]	44 a	29 a	199 e	48 a	29 a
5	50 b	41 a	26 a	84 c	44 a	36 ab
10	14 a	48 a	28 a	27 a	48 a	33 a
	Virgin subsoil			Pasture subsoil		
0	119 d	56 ab	33 a	246 g	48 a	31 a
5	30 a	98 c	54 c	26 a	54 ab	50 bc
10	22 a	78 b	54 c	30 a	42 a	57 c

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[1] Data for second harvest.

[2] Average of four P levels and four replications.

[3] Values followed by the same lower case letter within each respective micronutrient are not significantly different at 0.05 probability level.

soil at 0, 5, and 10 T/ha lime levels were 227, 50, and 14 ppm, respectively. Average increases of Zn and Cu concentrations in the forage from the limed over the unlimed subsoils were, at most, 22 (Zn) and 26 (Cu) ppm.

Zinc and Cu concentrations in the forage were significantly decreased by P applications (Table 24). This decrease was possibly due to the dilution effect of larger dry matter produced with P fertilization.

Where no lime was applied to the soils, Mn concentrations in the forage decreased consistently with increased P levels. The effect of P levels on forage Mn concentrations, however, disappeared by liming the soils especially at the 10 T/ha lime level.

The data in Tables 23 and 24 suggested that the lower forage yields obtained by liming the Los Diamantes soils were possibly due to marked depression of soil Mn availability. It is well known that plant available Mn^{++} becomes oxidized and transmutated to unavailable forms through chemical and biological processes as soil pH increases. Application of micronutrients in the soil did not alleviate the detrimental effect of lime on the third and fourth forage harvests. The rate of Mn applied to the soil (2.5 ppm/harvest) was probably not adequate to overcome Mn deficiency in the limed soils or the applied Mn was, upon contact with the soil, transformed immediately to unavailable forms.

Soil P fractions.--The Al-P and Ca-P in the soil, after the fourth harvest, increased directly with levels of applied lime and P (Tables 25 and 26). Calcium P, however, was not affected as markedly as Al-P. Lime increased Al-P particularly at the P_3 treatment, while lime significantly reduced the amount of Fe-P formed with P fertilization. The magnitude of decrease in Fe-P, however, was not high and disappeared at the highest P level.

Table 24.—Effect of lime and P levels on micronutrient concentrations in pangolagrass forage.[1]

	P levels (kg/ha)			
levels (T/ha)	0	50	100	150
	ppm			
		Mn		
0	258[2,3] h	209 g	175 f	147 a
5	61 d	48 cd	41 bc	36 abc
10	29 ab	20 a	19 a	23 ab
Avg.	116 x	92 y	78 z	69 z
		Zn		
0	72 b	43 a	41 a	40 a
5	119 c	44 a	38 a	37 a
10	98 c	42 a	34 a	41 a
Avg.	96 x	43 y	38 y	39 y
		Cu		
0	42 b	27 ab	27 ab	27 ab
5	75 c	26 a	28 ab	33 ab
10	83 c	30 ab	28 ab	30 ab
Avg.	67 x	28 y	27 y	30 y

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[1] Data for second harvest.

[2] Average of four soils and four replications.

[3] Values followed by the same lower case letter within the lettered groups a-g and x-z of each respective micronutrient are not significantly different at 0.05 probability level.

Table 25.--Effect of lime and P levels on soil P fractions after four pangolagrass forage harvests.[1]

Lime levels (T/ha)	P levels (kg/ha) 0	50	100	150	Avg.
	ppm				
			Al-P		
0	238 b[2]	250 c	258 cde	274 f	255 x
5	225 a	233 ab	274 f	287 g	255 x
10	236 b	253 cd	268 ef	296 g	263 y
			Fe-P		
0	222 bc	233 cd	243 de	247 e	236 z
5	219 b	224 bc	232 cd	238 de	228 y
10	206 a	221 b	225 bc	247 e	225 x
			Ca-P		
0	93 ab	95 bc	97 bcd	97 bcd	95 x
5	90 a	98 cde	100 def	103 e	98 y
10	94 abc	97 bcd	102 ef	101 def	99 y

[1] Average of four soils and four replications.

[2] Values followed by the same lower case letter within the lettered groups a-g and x-z of each respective P fraction are not significantly different at 0.05 probability level.

Table 26.--Effect of P levels on soil P fractions after four pangolagrass forage harvests.[1]

P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil	Avg.
	ppm				
			Al-P		
0	260 c[2]	79 a	252 c	341 g	233 w
50	279 d	90 a	259 c	355 h	246 x
100	306 e	104 b	280 d	376 i	267 y
150	322 f	112 b	307 e	402 j	286 z
Avg.	292 m	96 k	274 l	368 n	
			Fe-P		
0	254 f	213 c	201 ab	196 a	216 w
50	262 fg	231 d	210 bc	201 ab	226 x
100	272 g	242 e	213 c	207 bc	233 y
150	285 h	251 e	229 d	211 bc	244 z
Avg.	268 n	234 m	213 l	204 k	
			Ca-P		
0	122 g	61 a	93 c	94 c	93 w
50	125 gh	64 ab	98 d	99 d	97 x
100	131 i	64 ab	102 df	103 df	100 y
150	128 hi	68 b	100 df	106 f	100 y
Avg.	127 n	64 k	98 l	100 m	

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[1] Average of three lime levels and four replications.

[2] Values followed by the same lower case letter within the lettered groups a-j, k-n, and w-z of each respective P fraction are not significantly different at 0.05 probability level.

There was no significant effects of lime and P levels on soil organic P after a 7-month period (Table 27) as indicated by the analysis of variance (see appendix, Table 74). Organic P was appreciably lower after than before the experiment was conducted. The organic P contents of untreated soils, at the end of 7 months, had decreased by the following magnitudes: virgin surface, 355, virgin subsoil, 316; pasture surface, 315, and pasture subsoil, 123 ppm P. The magnitudes of decrease were unusually high and possibly were unrealistic.

The soils were extracted with 0.5 N NaOH following a concentrated HCl pretreatment. Organic matter in the alkaline-acid extract mixture was oxidized and the difference between the inorganic P before and after organic matter oxidation represented the organic P. The release of orthophosphate from organic matter by acid hydrolysis before the initial inorganic P could be determined, possibly gave a negative interference with the organic P determination. If this was the case, the data in Table 27 would indicate that the soil organic matter was altered to the extent that it became less acid resistant. Organic matter in the pasture subsoil must have been more resistant to decomposition, hence it was affected less by acid hydrolysis.

When organic matter decomposes, P is mineralized and should become available to plants if not fixed by the soil. Results from the subsoils, however, showed that forage yields from the P_0 treatment remained extremely low for all harvests (see appendix, Table 59). This indicated that there was no release of P from the organic forms or that the amount released was very low.

Experiment 2

The depressing effects of lime on pangolagrass forage yields and low P forage concentrations were unexpected results obtained from the

Table 27.--Effect of lime and P levels on the soil organic P fraction after four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
		ppm			
Before experiment[1]		1,002	649	1,198	865
0	0	647[2]	333	883	742
	150	714	223	942	729
	Avg.	680	278	913	735
5	0	630	296	821	763
	150	565	308	879	774
	Avg.	598	302	850	768
10	0	650	257	925	767
	150	468	215	859	700
	Avg.	564	306	892	733

[1] Data from Table 5.

[2] Average of four replications.

previous experiment. Whether these results applied to other forage plants, specifically legumes, was of great interest. Pigeon pea, therefore, was planted on the same soils used in Experiment I. The same treatments were maintained to study further the effects of lime and P levels on plant growth.

Forage yields.--The virgin soils produced significantly higher pigeon pea forage yields than the corresponding pasture soils, and the yields from the surface soils were significantly higher than yields from the subsoils. Significant yield increases were obtained with P application in all soils except in the pasture-surface soil. In contrast to the pangolagrass, pigeon pea growth was not suppressed by lime applications (Table 28) and in some cases (P_2 and P_3 treatments), lime seemed to be beneficial to the growth of pigeon pea (Fig. 9). However, increases in yields in the limed over the unlimed soils were not significant. It is possible that forage yield increases due to lime, at the P_2 and P_3 treatments, would have been statistically significant if the plants had been allowed to grow longer than 60 days.

Root weights were not appreciably increased by P applications. Roots were larger in the unlimed than in the limed soils, particularly at the P_0 and P_1 treatments (Table 29). Root weights were higher in the pasture soil than in the virgin soil. This result was not in accord with that obtained for the forage. Microbial activity, as indicated by a nitrification rate study with Los Diamantes soils by Gomez,[1] was found to be appreciably higher in the pasture than in the virgin soils. Although pigeon pea seeds were inoculated with a

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[1] Gomez, R. E. 1968. Nitrogen status of two alluvial soils from the humid tropics of Costa Rica. Thesis. Univ. Florida, Gainesville.

Table 28.--Effect of lime and P levels on pigeon pea forage yields following four pangolagrass forage harvests.

Lime levels	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil	Avg.
(T/ha)			g/pot		
0	4.53 b[1]	2.92 ab	3.75 ab	2.38 a	3.39 k
5	3.88 ab	3.34 ab	3.93 ab	2.52 ab	3.42 k
10	4.03 ab	3.44 ab	3.88 ab	3.11 ab	3.61 k
P levels (kg/ha)					
0	3.32 d	2.29 c	3.46 de	1.79 c	2.71 k
50	3.73 def	3.18 d	3.44 de	2.33 c	3.17 l
100	4.72 g	3.73 def	4.13 efg	3.42 d	4.00 m
150	4.81 g	3.73 def	4.38 ef	3.14 d	4.01 m
Avg.	4.14 y	3.23 x	3.85 y	2.67 w	

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[1] Values followed by the same lower case letter within the lettered groups ab, c-g, k-m, and w-y are not significantly different at 0.05 probability level.

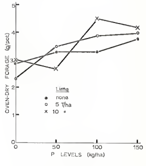

Fig. 9.--Effect of lime and P levels on pigeon pea forage yields following four pangolagrass forage harvests.

Table 29.--Effect of lime and P levels on pigeon pea root weights following four pangolagrass forage harvests.

Soils	Lime levels (T/ha) 0	5	10	Avg.
	----------	----------	g/pot ----------	----------
Virgin surface	1.18 cde[1]	0.89 ab	0.85 a	0.97 x
Virgin subsoil	1.02 abc	0.93 ab	0.99 abc	0.98 x
Pasture surface	1.30 e	1.17 cde	1.06 bc	1.17 y
Pasture subsoil	1.24 de	1.05 bcd	1.08 bc	1.13 y
P levels (kg/ha)				
0	1.10 hi	0.82 f	0.86 f	0.93 m
50	1.30 j	0.94 fh	0.84 f	1.04 m
100	1.13 ij	1.17 ij	1.17 ij	1.15 o
150	1.21 ij	1.07 hi	1.11 hi	1.13 o
Avg.	1.18 l	1.01 k	0.99 k	1.06

[1] Values followed by the same lower case letter within the lettered groups a-e, f-j, k-l, m-o, and x-y are not significantly different at 0.05 probability level.

Rhizobium and root nodules were formed in all treatments. It was possible that there were more microorganisms in the pasture than in the virgin soil which were effective in symbiotic N fixation. Consequently, there was better root development in the pasture soils without necessarily affecting forage growth because of the relatively short growth period.

Phosphorus concentrations.--Phosphorus concentrations in pigeon pea forage were relatively low (Table 30) and were similar to the values in the pangolagrass. Forage from the virgin soils consistently had higher P concentrations than that from the pasture soils. Phosphorus concentrations were appreciably higher in the roots than in the forage.

Table 30.--Phosphorus concentrations in pigeon pea forage and roots following four pangolagrass forage harvests.[1]

Soils	Forage	Root
	---------- % ----------	
Virgin surface	0.09 a[2]	0.13 e
Virgin subsoil	0.07 b	0.10 f
Pasture surface	0.06 c	0.12 g
Pasture subsoil	0.05 d	0.10 h

[1] Average of four P and three lime levels and four replications.

[2] Values followed by the same letter within the lettered groups a-d and e-h are not significantly different at 0.05 probability level.

Forage and root P concentrations significantly increased directly with levels of applied P (Table 31). In contrast to the pangolagrass, P concentrations in pigeon pea were significantly increased by lime application though differences were small. Forage and root P concentrations were higher in the limed soils than in the unlimed soils, especially at higher levels of applied P. This would explain why forage yields were higher in the limed than in the unlimed soils at the P_2 and P_3 treatments.

Pigeon pea forage from the surface soils contained more P than that from the subsoils (Table 32). More P was absorbed by plants from the virgin soils than from the pasture soils. Average P contents of the plants were increased by P applications from 1.67 mg/pot for the P_0 treatment to 3.36 mg/pot for the P_3 treatment.

Table 31.--Effect of lime and P levels on the P concentrations in pigeon pea forage and roots following four pangolagrass forage harvests.

Lime levels	P levels (kg/ha)				
	0	50	100	150	Avg.
(T/ha)	%				
			Forage		
0	0.06 b[1]	0.06 b	0.07 c	0.07 c	0.06 i
5	0.05 a	0.06 b	0.07 c	0.08 d	0.07 j
10	0.06 b	0.07 c	0.08 d	0.09 e	0.07 j
Avg.	0.05 u	0.06 u	0.07 v	0.08 w	0.07
			Root		
0	0.10 f	0.10 f	0.11 f	0.11 f	0.10 k
5	0.10 f	0.12 g	0.12 f	0.14 h	0.11 l
10	0.10 f	0.11 f	0.11 f	0.14 h	0.11 l
Avg.	0.10 x	0.11 y	0.11 y	0.13 z	0.11

[1] Values followed by the same letter within the lettered groups a-e, f-h, ij, kl, u-w, and x-z are not significantly different at 0.05 probability level.

Table 32.--Effect of P levels on the P contents of pigeon pea forage.

P levels	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil	Avg.
(kg/ha)	mg/pot				
0	2.79[1]	1.32	1.73	0.86	1.67
50	3.37	2.27	1.80	0.97	2.10
100	4.31	3.17	2.27	1.70	2.86
150	5.25	3.07	3.15	1.98	3.36
Avg.	3.93	2.46	2.24	1.38	2.50

[1] Average of three lime levels and four replications.

Calcium, Mg, and K concentrations.--Pigeon pea forage Ca, Mg, and K concentrations did not vary appreciably with the kind of soil (Table 33). Calcium concentrations were slightly higher than those in pangolagrass. Magnesium and K concentrations were lower in the pigeon pea than in pangolagrass. Potassium concentrations were only one-third those in the grass.

Table 33.--Calcium, Mg, and K concentrations in pigeon pea forage following four pangolagrass forage harvests.[1]

Soils	Ca	Mg	K
		%	
Virgin surface	1.19	0.25	1.01
Virgin subsoil	1.19	0.17	1.01
Pasture surface	1.32	0.19	1.06
Pasture subsoil	1.06	0.14	0.93

[1] Average of three lime and four P levels, and four replications.

Calcium and K concentrations in pigeon pea forage were increased by lime applications while Mg concentrations were decreased (Table 34). Forage K concentrations from the limed soils were higher, possibly because the previous grass crop from the limed soils did not absorb as much K as that from the unlimed soils. Calcium concentrations of pigeon pea forage decreased with increased P levels, in contrast to the Ca concentrations of pangolagrass, which were increased by P applications.

Micronutrient concentrations.--Concentrations of Mn in the pigeon pea forage and roots were significantly decreased by lime applications while Zn and Cu concentrations were not affected (Table 35). Manganese, Zn, and Cu concentrations were higher in the roots than in the forage.

Table 34.--Effect of lime and P levels on the Ca, Mg, and K concentrations in pigeon pea forage following four pangolagrass forage harvests.[1]

Lime levels (T/ha)	P levels (kg/ha) 0	50	100	150	Avg.
	----------	----------	%	----------	----------
			Ca		
0	1.25	1.01	0.90	0.87	1.01
5	1.65	1.20	1.13	0.98	1.24
10	1.68	1.61	0.98	1.05	1.33
Avg.	1.53	1.27	1.00	0.97	1.19
			Mg		
0	0.21	0.21	0.22	0.23	0.22
5	0.19	0.19	0.18	0.20	0.19
10	0.13	0.16	0.17	0.17	0.16
Avg.	0.18	0.19	0.19	0.20	0.19
			K		
0	0.95	0.91	0.92	0.77	0.89
5	0.96	1.02	0.98	1.00	0.99
10	1.21	1.25	0.99	1.08	1.13
Avg.	1.04	1.06	0.96	0.95	1.00

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[1] Average of four soils and four replications.

Table 35.--Effect of lime levels on the micronutrient concentrations in pigeon pea forage and roots.[1]

Lime levels	Forage			Root		
	Mn	Zn	Cu	Mn	Zn	Cu
(T/ha)	ppm					
0	89 a[2]	44 a	19 a	202 a	63 a	52 a
5	37 b	44 a	19 a	90 b	65 a	50 a
10	21 c	44 a	20 a	82 c	64 a	53 a

[1] Average of four soils, four P levels, and four replications.

[2] Values followed by the same letter within each respective micronutrient are not significantly different at 0.05 probability level.

Phosphorus application did not change appreciably the concentrations of Zn and Cu in the forage or roots (Table 36). The slight decline of Zn and Cu with increase in P levels was attributed to the dilution effect of larger dry matter produced.

Table 36.--Effect of P levels on the Zn and Cu concentrations in pigeon pea forage and roots.[1]

P levels	forage		root	
	Zn	Cu	Zn	Cu
(kg/ha)	ppm			
0	46	19	65	54
50	43	20	65	52
100	42	19	63	52
150	44	19	62	49

[1] Average of three lime levels, four soils, and four replications.

In contrast to the Zn and Cu concentrations, there was a significant effect of lime x P interaction on Mn concentrations in the forage and roots (Table 37). In the forage, Mn concentrations decreased with P levels where no lime was applied to the soils. The effect of P on Mn concentrations disappeared by liming the soils, especially at the 10 T/ha lime level. These results were in agreement with those obtained from the pangolagrass. In contrast to the forage, Mn concentrations in the roots from the limed soils increased directly with lime levels. This suggested that the translocation of Mn to the tops was inhibited by P.

Table 37.--Effect of lime and P levels on Mn concentrations in pigeon pea forage and roots.[1]

Lime levels (T/ha)	P levels (kg/ha) 0	50	100	150
	ppm			
			Forage	
0	152 e[2]	80 d	60 c	63 c
5	57 c	35 b	25 a	31 a
10	21 a	21 a	22 a	21 a
			Root	
0	344 o	202 n	126 lm	135 m
5	87 jk	81 jk	91 jkl	99 kl
10	50 i	66 ij	99 kl	114 lm

[1] Average of four soils and four replications.

[2] Values followed by the same lower case letter within the lettered groups a-e and i-o are not significantly different at 0.05 probability level.

Although Mn concentrations in pigeon pea forage were affected by lime similarly to those in the pangolagrass forage, pigeon pea forage yields were not adversely affected as were grass yields. This may have been the result of a lower Mn requirement of pigeon pea than the grass. Average Mn concentrations in pigeon pea were one-fourth those in the grass.

Experiment 2

At the time this experiment was initiated, there were no chemical analyses available to explain the differential effect of lime on pangolagrass and pigeon pea growth. In Experiment 1, pangolagrass was planted 10 days after the lime was mixed with the soil. It was thought that the depressing effect of lime on growth might be overcome by allowing a longer time for the lime and soil to react. Therefore, pangolagrass was planted in the same soils used in Experiments 1 and 2 with the same treatments maintained, 12 months after the initial treatments.

Forage yields.--Pangolagrass forage yields were affected by lime and P applications in a manner similar to the effect in Experiment 1 (Fig. 10). Forage yields were decreased by increasing lime levels. There was a significant linear increase of forage yields, at all lime levels, with increased levels of applied P. This indicated that P applied 12 months before planting was available to the plants. It is possible that P applied to Los Olamanas soils could still be relatively available to plants for longer periods of time. The regression coefficients were all significant at 0.05 probability level. The lime x P interaction was not significant.

Phosphorus concentrations.--Forage P concentrations were relatively low (Table 38) and were the same as those obtained in Experiment 1

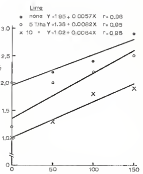

Fig. 10.--Effect of lime and P levels on pangolagrass forage yields following pigeon pea and four pangolagrass forage harvests.

(Table 15). Phosphorus concentrations were increased by P applications, especially in the virgin soils. Forage from the virgin soils had significantly higher P concentrations than that from the pasture soils. This would indicate further that P in the virgin soils was more available than in the pasture soils.

Table 38.--Effect of P levels on the P concentrations in pangolagrass forage following pigeon pea and four pangolagrass forage harvests.

	P levels (kg/ha)				
Soils	0	50	100	150	Avg.
	%				
Virgin surface	0.07[1] d[2]	0.08 e	0.07 d	0.09 f	0.08 l
Virgin subsoil	0.06 c	0.07 d	0.07 d	0.08 e	0.07 k
Pasture surface	0.04 a	0.05 b	0.05 b	0.05 b	0.05 j
Pasture subsoil	0.04 a	0.04 a	0.05 b	0.06 c	0.05 j
Avg.	0.05 g	0.06 h	0.06 h	0.07 i	0.06

[1] Average of three lime levels and three replications.

[2] Values followed by the same letter are not significantly different at 0.05 probability level.

Relatively little P was absorbed by the grass in this experiment (Table 39). Forage P contents were increased by P application and they were higher in the virgin soils than in the pasture soils.

Phosphorus recovery.--The percent P recoveries from the applied fertilizer by all forage harvests in Experiments 1, 2, and 3 are shown in Table 40. These data represent only the percent recoveries from the unlimed soils where the highest forage yields were obtained. Percent P recoveries ranged from 7 to 19% of that applied. The trend of results was similar to that obtained in Experiment 1 (Table 18).

Table 39.--Effect of P levels on the P contents of pangolagrass forage following pigeon pea and four pangolagrass forage harvests.

P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil	Avg.
	mg/pot				
0	1.33[1]	0.62	2.21	0.44	1.15
50	1.95	1.06	0.96	0.55	1.13
100	1.75	1.67	1.11	0.70	1.31
150	2.07	2.06	1.65	0.94	1.68
Avg.	1.78	1.35	1.48	0.66	1.32

[1] Average of three lime levels and three replications.

Table 40.--Percent P recovery from applied fertilizer by all forage harvests in Experiments 1, 2, and 3.

P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
	%			
0	--	--	--	--
50	14	15	7	12
100	19	16	7	11
150	12	18	9	8

Micronutrient concentrations.--Forage Zn, Cu, and Fe concentrations were, in general, not affected by lime and P applications while Mn concentrations were markedly reduced (Table 41). Average Mn concentrations in the forage were as follows: unlimed soils, 491, 5 T lime/ha, 73, and 10 T lime/ha, 16 ppm. Results obtained from this experiment were consistent with those from Experiment 1. The data in Table 41 further indicated that the possible cause of depressed pangolagrass growth in the limed soils was Mn deficiency. However, there were no visual nutrient deficiency symptoms in the plants.

Table 41.--Effects of lime and P levels on the micronutrient concentrations in pangolagrass forage following pigeon pea and four pangolagrass forage harvests.

Lime levels (T/ha)	Mn	Zn	Cu	Fe
	ppm			
0	491[1] a[2]	31 a	37 a	39 a
5	73 b	32 a	38 a	37 a
10	16 c	31 a	38 a	41 a
P levels (kg/ha)				
0	250[3] d	32 d	37 d	39 d
50	184 e	32 d	39 d	38 d
100	179 e	32 d	36 d	38 d
150	161 e	32 d	41 d	41 d

[1] Average of four soils, four P levels, and three replications.

[2] Values followed by the same letter within the lettered groups a-c and de are not significantly different at 0.05 probability level.

[3] Average of four soils, three lime levels, and three replications.

Optimum P Level x Lime Experiment

Forage yields.--The total forage yields from four pangolagrass harvests in the pasture-surface soil are shown in Fig. 11. Forage yields from the limed soil were significantly lower than yields from the unlimed soil, especially at the higher P levels. In both lime treatments, yields were increased significantly by P applications. Forage yield responses to applied P were described by the following quadratic equations:

unlimed soil, $Y = 10.9 + 0.023\,X - 0.14(10^{-4})\,X^2$

and limed soil, $Y = 9.0 + 0.020\,X - 0.17(10^{-4})\,X^2$

where Y was the yield and X was the level of P applied. The regression coefficients were significant at the 0.05 probability level.

In order to determine the applied P needed for maximum yield, the quadratic equations were differentiated, equated to zero, and solved for X. The calculated levels of P needed for maximum yield were high unlimed soil, 820 kg P/ha and limed soil, 590 kg P/ha.

Phosphorus concentrations.--The forage P concentrations were increased appreciably by P applications (Fig. 12). In the unlimed soil, P concentrations increased from 0.05% for the control to 0.09% for the 450 kg/ha P level. Phosphorus concentrations did not increase above 0.09% until the level of applied P had been increased to 900 kg/ha. The increased P concentration at the highest P level could have been the result of the decline in forage yields. Phosphorus concentrations in the forage from the limed soil were in most cases higher than those from the unlimed soil. This was probably due to less dilution because of lower dry matter yields from the limed soil. Considerable fluctuations in P concentrations characterized the forage from the limed soil because of yield variations.

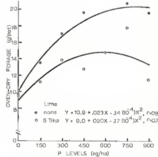

Fig. 11.--Pangolagrass forage yield response to P and lime applied to pasture-surface soil.

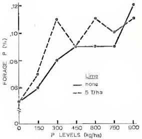

Fig. 12.--Forage P concentrations in pangolagrass from pasture-surface soil as affected by P and lime levels.

The forage P concentration from the unlimed pasture-surface soil, where maximum yields were obtained, was 0.09% (Figs. 11 and 12). This concentration represents the "critical percentage" in the plant above which luxury consumption occurs. Phosphorus concentrations obtained in this greenhouse experiment, as in previous experiments, were appreciably lower than those reported from field experiments or pastures. Vicente-Chandler (180) reported that the average P concentration of pangolagrass from a well managed pasture in Puerto Rico was 0.24%. However, Vicente-Chandler sampled the grass for P analysis by plucking so as to simulate grazing, while in this study, all above ground vegetative parts were analyzed. Grass stolons normally lie on the soil surface and only a few would be included during sampling in the field. Vicente-Chandler further reported that the P concentrations of different grasses, including pangolagrass, sampled from field experiments varied from 0.19 to 0.36% P depending on the rate of N applied.

Gomide *et al.* (78) reported that the forage P concentrations of six tropical grasses studied in Brazil were 0.26% at 4 weeks and 0.12% at 36 weeks of age. Pangolagrass appeared to be the poorest source of P for grazing cattle at all ages studied (average, 0.12% P). The forage P concentrations of pangolagrass varied from 0.08 to 0.17% depending on age. The data of Gomide *et al.* were obtained from forages sampled by clipping the grasses from field experiments.

However, Blue (23) found that the application of P (0 to 88 ppm) to Puleton loamy fine sand of British Honduras gave P concentrations of pangolagrass that varied from 0.03 to 0.07%. Blue's data were obtained from a replicated pot study where the foliage and stolons were harvested and analyzed collectively. The differences in the method of sampling plant materials for chemical analysis, in addition to differences in soil and environmental conditions would, therefore, limit direct comparisons of values obtained by various workers.

Phosphorus recovery.--The percentages of applied P recovered by four pangolagrass forage harvests were relatively small (Table 42). They varied from 3.4 to 11.6% depending on the lime and P level. Phosphorus recovery percentages from the unlimed surface soil were higher than those from the limed soil. The highest percent recovery was obtained from the 300 kg/ha P application. There was an appreciable decline in percentage P recovery with P levels beginning at 450 kg P/ha level, especially from the limed soil.

Table 42.--Effect of lime and P levels on the P contents and percent P recovered by four pangolagrass forage harvests from fertilizer applied to the pasture-surface soil.

P levels	No Lime		5 T/ha	
	P content	P recovered	P content	P recovered
(kg/ha)	mg/pot	%	mg/pot	%
0	-	-	-	-
150	12.6	8.4	12.0	8.0
300	34.7	11.6	42.2	14.1
450	50.4	11.2	26.8	5.6
600	35.9	6.0	46.1	7.7
750	54.9	7.3	52.1	6.9
900	77.4	8.6	30.7	3.4

Micronutrient concentrations.--Concentrations of Mn, Zn, and Cu in the forage were not significantly affected by P applications

(Table 43) as indicated by the analysis of variance in Table 85 of the appendix. As in previous experiments, lime markedly decreased the forage Mn concentrations. Forage Zn concentrations were reduced by liming the soil which was not the case in the other experiments with pangolagrass. Forage Cu concentrations were not significantly affected by lime. There was no significant lime x P interaction effect on Mn, Zn, and Cu concentrations.

The induction of Zn deficiency in plants as a result of high levels of available soil P or rates of applied P is well known. Results reported by Burleson and Page (32) indicated that P and Zn react together within the roots in a manner that reduces either their mobility or solubility. It is possible that Zn could react with applied P in the soil. In this study, however, no Zn x P interaction was obtained.

Three successive weekly sprayings of 20 ppm Mn on the grass did not alleviate the depressing effect of lime on plant growth although the concentrations of Mn in the sprayed plants were markedly increased, especially with plants in the limed soil (Table 44). It was possible that the sprayed Mn was not absorbed by the plant and remained on the leaf and stolon surfaces, consequently, no beneficial effect was obtained. It should be mentioned, however, that $MnSO_4$ has been used to correct Mn deficiencies in plants, especially with several foliar applications (44).

Soil P fractions.--Data in Fig. 13 showed that most of the added P was formed as Al-P and a relatively small portion was formed as Fe-P especially at the higher P levels. Lime did not have a significant effect on Fe-P or Ca-P. The data showed that where lime was not

Table 43.--Effect of lime and P levels on the micronutrient concentrations in pangolagrass forage from the pasture-surface soil.[1]

Lime levels (T/ha)	P levels (kg/ha)	Mn	Zn	Cu
		------------	ppm	------------
0	0	310[2]	41	31
	150	362	43	36
	300	381	45	47
	450	352	42	41
	600	343	43	55
	750	354	41	63
	900	378	40	66
	Avg.	354 x[3]	42 x	48 x
5	0	117	39	32
	150	133	32	40
	300	139	34	46
	450	113	33	41
	600	78	33	46
	750	112	34	47
	900	103	29	32
	Avg.	113 z	33 z	40 x

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[1] Data from third harvest.

[2] Average of four replications.

[3] Values followed by the same letter are not significantly different at 0.05 probability level.

Table 44.--Effect of sprayed Mn[1] on the forage Mn concentrations and pangolagrass forage yields from limed and unlimed pasture-surface soil.

Lime levels	Forage yields		Mn concentrations	
	Unsprayed	Sprayed	Unsprayed	Sprayed
(T/ha)	------- g/pot -------		-------- ppm --------	
0	5.05[2] b[3]	4.76 b	407 c	561 d
5	4.17 ab	2.99 a	144 a	272 b

[1] Solution concentration is 20 ppm Mn as $MnSO_4 \cdot H_2O$.

[2] Average of two replications.

[3] Values followed by the same letter within forage and Mn columns are not significantly different at 0.05 probability level.

applied, especially at the higher P levels, large amounts of the applied P were in relatively insoluble forms. Water-soluble P was, in all cases, negligible and was not included in the data.

The Fe-P and Ca-P did not change appreciably with time while Al-P was appreciably higher at 176 days than at 43 days after P was applied to the soil. There was slightly less Fe-P extracted from the limed soil after 176 days than after 43 days. The result obtained with Al-P was quite surprising because it has been reported that freshly formed Al-P crystallizes to less soluble forms or is converted to the Fe-P and occluded P with passage of time (98). It is suggested that the increase in Al-P obtained in this experiment was due to some P extracted from the organic matter by the 0.5 N NH_4F (pH 8.2) solution. This solution was possibly capable of extracting P from the organic

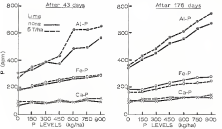

Fig. 13.--Effect of lime and P levels, and time on the inorganic P fractions in pasture-surface soil.

matter, especially at an alkaline pH, after the organic matter was altered microbiologically.

As almost all of the applied P was in the Al-P fraction (Fig. 13), and as pangolagrass responded to the applied P (Fig. 11) the Al-P formed in the soil from the fertilizer may have been the primary source of P for the plants. Furthermore, since lime enhanced the formation of Al-P from the fertilizer, pangolagrass forage growth should have been benefited if it had not been for the apparent lime-induced nutritional imbalance.

$CaCO_3$-$MgCO_3$ x P Experiment

Forage yields.--The effect of lime of different Ca and Mg ratios applied to the pasture-surface soil, on pangolagrass forage yields is shown in Table 45. Forage yields from chemically equivalent quantities of $CaCO_3$ and $MgCO_3$ (Treatment 4) were higher than the yields from the other lime treatments. In general, forage yields from the limed soils were lower than those from the unlimed soils except where P was not applied, in which case, the forage yield from Treatment 4 was higher than the control. Average yields from the different lime treatments did not differ significantly. The data indicated that pangolagrass was not benefited by liming the Los Olamantes soil with $MgCO_3$ alone or in combination with $CaCO_3$.

Soil pH.--Lime increased the pH of the pasture-surface soil, especially with the application of $MgCO_3$ (Table 46), and soil pH was slightly higher where triple superphosphate was applied. Soil pH varied from 5.2 to 5.9 depending on the lime and P treatment.

Table 45.--Effect of lime of different Ca and Mg compositions on pangolagrass forage yields from pasture-surface soil.

Lime treatment No.	Lime compositions CaCO$_3$	MgCO$_3$	P levels (kg/ha) 0	150	Avg.
	(% eq basis)			g/pot	
1	Control		5.5[1] ab[2]	12.9 a	9.2 h
2	100	0	4.1 a	9.8 cde	6.9 h
3	75	25	6.3 abc	8.0 bcd	7.1 h
4	50	50	6.9 abc	11.6 de	9.2 h
5	25	75	5.3 ab	8.9 bcd	7.1 h
6	0	100	5.3 ab	8.3 bc	6.8 h
	Avg.		5.5 f	9.9 g	

[1] Total of two harvests.

[2] Values followed by the same lower case within lime, P, and lime x P interaction cells are not significantly different at 0.05 probability level.

Table 46.--Effect of lime of different Ca and Mg compositions on pH of pasture-surface soil.

Lime treatment No.	P levels (kg/ha) 0	150
1	5.20	5.50
2	5.40	5.70
3	5.70	5.85
4	5.70	5.80
5	5.70	5.85
6	5.75	5.90

Phosphorus concentrations.--As in the previous experiments with pangolagrass, forage P concentrations were not significantly affected by lime applications (Table 47). Application of P to the soil increased the average P concentration in the forage from 0.04 to 0.06%.

Table 47.--Effect of lime of different Ca and Mg compositions on the P concentrations in pangolagrass forage.

Lime treatment No.	P levels (kg/ha)		
	0	150	Avg.
		%	
1	0.04	0.06	0.05
2	0.03	0.06	0.05
3	0.05	0.07	0.06
4	0.05	0.06	0.06
5	0.04	0.07	0.06
6	0.05	0.06	0.06
Avg.	0.04	0.06	0.05

Calcium and Mg concentrations.--Forage Mg concentrations increased while Ca concentrations decreased as more $MgCO_3$ and less $CaCO_3$ were added to the soil (Table 48). Magnesium concentrations were affected by lime treatments more than Ca concentrations. The data did not suggest an explanation for the depressing effect of lime on pangolagrass growth.

Micronutrient concentrations.--Forage from the limed soils had significantly lower Mn concentrations than that from the unlimed soil (Table 49). Zinc and Cu concentrations were not significantly affected by the lime treatments. Manganese concentrations in the forage from

Table 48.--Effect of lime of different Ca and Mg compositions on the Ca and Mg concentrations in pangolagrass forage.

Lime treatment No.	Ca	Mg
	-------- %	--------
1	0.27	0.29
2	0.33	0.32
3	0.32	0.39
4	0.29	0.43
5	0.24	0.46
6	0.21	0.52

Table 49.--Effect of lime of different Ca and Mg compositions on micronutrient concentrations in pangolagrass forage.

Lime treatment No.	P levels (kg/ha)					
	0	150	0	150	0	150
	----------------------	----------	ppm	----------	----------	----------------------
	Mn		Zn		Cu	
1	188 b[1]	181 b	36 a	47 a	42 a	85 b
2	63 a	46 a	32 a	45 a	41 a	68 ab
3	55 a	45 a	51 a	46 a	46 a	72 b
4	59 a	40 a	49 a	47 a	51 a	63 ab
5	62 a	45 a	37 a	42 a	38 a	61 ab
6	54 a	42 a	39 a	47 a	46 a	65 ab
Avg.	80 c	66 d	41 c	45 c	44 c	69 d

[1] Values followed by the same lower case letter within each micronutrient are not significantly different at 0.05 probability level.

the limed soils did not differ significantly. This would indicate that various combinations of $CaCO_3$ and $MgCO_3$ applied to the soil effected Mn availability in the same manner as when either $CaCO_3$ or $MgCO_3$ was applied alone. Forage yields (Table 45) and Mn concentrations (Table 49) showed that yields from the limed soil were not appreciably reduced by lime applications regardless of the fact that Mn concentrations in the forage were decreased significantly. The results from this experiment suggested that nutritional imbalances in the grass, in addition to Mn, were created by liming the Los Olamantes soils. Data from Mn experiments, which will be presented later, suggested that other nutrients may have been involved.

Lime x Micronutrient Experiments

Experiment 1

Forage yields and root weights.--Application of fritted micronutrients (FTE-503) at rates as high as 90 kg/ha did not alleviate the depressing effect of lime on pangolagrass forage growth (Table 50). For all harvests, the lime effects were significant at the 0.05 probability level while micronutrients and the lime x micronutrient interaction were not significant. In the fourth harvest, results obtained with the limed soils were difficult to interpret. Whereas yields from the 10 T/ha lime treatment appeared to increase directly with rates of FTE-503, there was no evidence of yield increases for the 5 T/ha lime treatment. Results obtained with root weights were similar to those for the forages.

Micronutrient concentrations.--Forage Mn, Zn, and Cu concentrations were determined only for the first and fourth harvests. Micronutrient concentrations in the forage were appreciably lower in the

Table 50.--Effect of lime and fritted micronutrients (FTE-503) on forage yields from four pangolagrass harvests and root weights.

Lime levels	FTE-503	Harvests				
		1	2	3	4	Root
(T/ha)	(kg/ha)	g/pot				
0	0	4.6	5.5	5.1	9.8	2.5
	30	3.8	6.1	7.5	11.9	3.4
	60	3.9	5.4	6.4	8.4	2.7
	90	3.1	4.3	5.5	8.5	1.4
	Avg.	3.8 a[1]	5.3 a	6.1 a	9.6 a	2.5 a
5	0	1.8	4.2	3.9	5.8	1.3
	30	1.8	1.5	1.8	5.0	0.8
	60	1.7	1.5	1.4	5.6	0.5
	90	1.7	2.4	2.8	5.1	0.9
	Avg.	1.7 b	2.4 b	2.5 b	5.4 b	0.9 b
10	0	1.2	2.3	2.2	5.0	0.7
	30	1.4	3.4	2.8	4.9	0.6
	60	1.4	3.6	3.7	7.6	0.9
	90	1.2	3.3	3.4	7.9	1.2
	Avg.	1.3 c	3.1 b	3.0 b	6.3 b	0.8 b

[1] Values followed by the same letter within each column are not significantly different at 0.05 probability level.

first than in the fourth harvest, especially for Mn (Table 51). Forage Cu concentrations were not significantly affected by lime and FTE-503 applications. Zinc concentrations were decreased by lime only at the fourth harvest.

In the unlimed soil, micronutrients from the FTE-503 material were immediately available to the plants as indicated by the forage Mn and Zn concentrations in the first harvest. As in the previous experiments, Mn concentrations were decreased markedly by lime applications. In the fourth harvest, however, Mn concentrations in the forage from the 5 T/ha lime treatment were relatively high. Forage Mn concentrations from the 10 T/ha lime treatment remained at low levels in the first and fourth harvests.

In spite of the high Mn concentrations in forage from the fourth harvest with the 5 T/ha lime treatment, yields from the limed soil were significantly lower than those from the unlimed soil. Forage Mn concentrations from the 5 T/ha lime treatment should have been adequate to meet the Mn requirement of the grass. Fitts[1] found that Mn concentrations in oven-dry pangolagrass were decreased to low values (15 ppm) by liming Rex fine sand in Florida. Forage yields in the limed soil appeared to be lower but were not significantly different from the control (201 ppm Mn). Melsted et al. (132) reported the following critical values of Mn in the leaves of several crops at definite growth stages: corn, 15, soybeans, 20, wheat, 30, and

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[1] Fitts, J. B. 1968. The relative availability of Mn to plants from several Mn sources, applied as fertilizer. Thesis. Univ. of Florida, Gainesville. 67 p.

Table 51.--Effect of lime and FTE-503 applications to pasture-surface soil on the micronutrient concentrations in pangolagrass forage.

Lime levels (T/ha)	FTE-503 (kg/ha)	Harvests					
		1	4	1	4	1	4
		ppm					
		Mn		Zn		Cu	
0	0	108 d[1]	209 c	61 ab	85 d	38 a	64 a
	30	114 d	275 d	63 abc	74 c	39 a	55 a
	60	113 d	236 cd	65 abc	77 cd	36 a	63 a
	90	130 e	228 c	78 af	63 b	33 e	63 e
	Avg.	116 x	237 x	67 x	75 x	36 x	61 x
5	0	44 c	110 b	80 f	61 b	34 e	69 ab
	30	36 c	128 b	61 ab	60 b	35 a	59 a
	60	40 c	112 b	68 abcde	63 b	31 e	54 e
	90	40 c	125 b	60 a	62 b	33 e	83 b
	Avg.	40 y	118 y	67 x	61 y	33 x	66 x
10	0	19 a	25 a	71 bcdef	55 ab	30 e	55 e
	30	21 ab	24 a	66 abcd	46 a	29 e	59 a
	60	18 e	23 e	72 cdef	50 a	38 a	66 ab
	90	28 b	19 a	77 def	50 e	40 e	66 eb
	Avg.	21 z	23 z	71 x	50 z	34 x	62 x

[1] Values followed by the same lower case letter within each column of the lettered groups a-f and x-z are not significantly different at 0.05 probability level.

alfalfa, 25 ppm. According to Yamasaki (193), rice requires 10 times as much Mn as barley and wheat. Misra (137) observed Mn deficiency symptoms in young leaves of sweet potatoes where Mn concentrations were less than 25 ppm in the blades and 18 ppm in the petioles. Maximum growth of sweet potatoes was obtained in plants with Mn concentrations between 25 and 60 ppm in the blades, and 20 and 30 ppm in the petioles.

Critical values for certain nutrients, below which plant growth will respond to fertilizer application,are difficult to determine. This is due to the fact that variations in plant composition may result from differences in age and kind of plant, nutrient levels and ratios, seasonal changes, and various other factors (132). It is possible that pangolagrass requires a high concentration of Mn in the tissue under optimum conditions.

The Mn data suggested the possibility of other micronutrient deficiencies such as B, or toxicities such as Mo, which are induced by lime application. In the case of B, it was reported that cereal crops require only one-thirtieth the amount required by leguminous crops (193). If B was deficient in the limed Los Diamantes soils, pigeon pea logically should have been adversely affected by lime application. Since this was not the case, the depressing effect of lime on pangolagrass yields was probably not due to B deficiency. It is difficult to interpret the lime results from pangolagrass in terms of Mo or other micronutrients not discussed earlier because of limited information presently available. It should be pointed out that FTE-503 contains 3% B and 0.2% Mo.

Experiment 2

Forage yields.--As in the earlier experiments with pangolagrass, forage yields were significantly lower in the limed than in the unlimed pasture-surface soil (Table 52). The Mn chelate applied to the limed soil did not affect forage yields. In the unlimed soil, forage yields were significantly decreased when Mn chelate was applied at the rate of 60 kg/ha Mn.

Table 52.--Effect of lime and Mn (Mn chelate)[1] levels on pangolagrass forage yields from pasture-surface soil.

Lime levels (T/ha)	Mn levels (kg/ha) 0	60	120	Avg.
	g/pot			
0	8.3 c[2]	6.6 b	7.4 bc	7.4 f
5	3.4 a	3.9 a	4.6 a	4.0 a
10	4.6 a	2.9 a	3.6 a	3.7 a
Avg.	5.4 d	4.5 d	5.2 d	5.0

[1] Mn source was Mn-NTA-2 (8.2% Mn) manufactured by Monsanto Co., St. Louis, Mo.

[2] Values followed by the same letter within lime, Mn, and lime x Mn interaction cells are not significantly different at 0.05 probability level.

Micronutrient concentrations.--Forage Mn concentrations were appreciably higher in the unlimed than in the limed soil (Table 53). Manganese concentrations were increased markedly by the Mn chelate applications in the unlimed soil especially with 60 kg/ha Mn level. Manganese concentrations were also increased by Mn chelate applications to the 5 T/ha lime treatment, but increases were not as high as

Table 53.--Effect of lime and Mn chelate on the Mn and Fe concentrations in pangolagrass forage.

Lime levels (T/ha)	Mn levels (kg/ha) 0	60	120	Avg.
	ppm			
		Mn		
0	460 b[1]	700 c	767 c	642 e
5	133 a	153 a	177 a	154 f
10	63 a	67 a	47 a	59 g
Avg.	219 c	307 d	330 d	285
		Fe		
0	37 a	37 a	37 a	36 c
5	38 a	45 a	42 a	42 c
10	40 a	35 a	40 a	38 c
Avg.	38 b	39 b	38 b	37

[1] Values followed by the same letter within lime, micronutrient, and lime x micronutrient interaction cells are not significantly different at 0.05 probability level.

in the unlimed soil. Manganese from the chelate was not available at the 10 T/ha lime treatment. Iron concentrations in the forage were not affected by high levels of Mn applied.

Experiment 3

Forage yields.--The addition of 0, 50, and 100 kg/ha Mn as $MnSO_4.H_2O$ to the 0, 60, and 120 kg/ha Mn from Mn chelate, respectively, of the preceding experiment did not improve pangolagrass growth in the limed soils (Table 54). Forage yields were not significantly affected by Mn applications at any lime level.

Table 54.--Effect of lime and Mn ($MnSO_4.H_2O$) levels on the pangolagrass forage yields following the first harvest treated with Mn chelate.

Lime levels	Mn levels (kg/ha)[1]			
	0	110	220	Avg.
(T/ha)	----------------	g/pot	----------------	
0	8.7 b[2]	7.4 b	7.8 b	8.0 e
5	3.7 a	4.7 a	5.1 a	4.5 d
10	4.8 a	4.1 a	4.5 a	4.4 d
Avg.	5.7 c	5.4 c	5.8 c	5.6

[1] Manganese levels indicated were totals after adding 0, 50, and 100 kg/ha Mn as $MnSO_4.H_2O$ to the 0, 60, and 120 kg/ha Mn as Mn chelate treatments, respectively of the preceding experiment.

[2] Values followed by the same letter within lime, micronutrient, and lime x micronutrient interaction cells are not significantly different at 0.05 probability level.

Micronutrient concentrations.--Iron concentrations in the forage were not affected by the additional $MnSO_4.H_2O$ applications (Table 55). Manganese concentrations were markedly increased by Mn applications except in forages from the 10 T/ha lime level. Manganese concentrations in the forage from the 5 T/ha lime level were high and were about one-half those from the unlimed soil. The relatively high Mn concentrations shown in Tables 53 and 55 for the 5 T/ha lime level further suggested that nutritional factors other than Mn deficiency may have been involved with pangolagrass growth in the limed soils. Further work, therefore, is needed to elucidate the problem encountered with pangolagrass grown on limed Los Olamantes soils.

Table 55.--Effect of lime and $MnSO_4 \cdot H_2O$ on the Mn and Fe concentrations in pangolagrass forage following the first harvest treated with Mn chelate.

Lime levels (T/ha)	Mn levels (kg/ha) 0	110	220	Avg.
	ppm			
		Mn		
0	309 c[1]	498 d	546 d	451 h
5	208 b	221 b	257 bc	229 i
10	58 a	55 a	55 a	56 j
Avg.	192 e	258 f	286 f	245
		Fe		
0	30 a	30 a	26 a	28 d
5	36 a	31 a	28 a	32 d
10	30 a	31 a	23 a	28 d
Avg.	32 b	31 b	26 c	29

[1] Values followed by the same letter within each nutrient element of the lime, Mn, and lime x Mn interaction cells are not significantly different at 0.05 probability level.

Silica-Organic Matter Experiment

Forage yields and root weights.--In the first harvest, the addition of S. humilis, Ca silicate, and rice hulls significantly increased pangolagrass forage yields over those of the control (Table 56). In the second harvest, S. humilis (5 T/ha) and rice hull (0.47 T/ha Si) treatments gave significantly increased forage growth. Although forage yields from the S. humilis (10 T/ha), Ca silicate, and rice hull (1.41 T/ha Si) treatments were higher than those from the control, the yield differences were not statistically significant. In the third and fourth harvests, the yields from the S. humilis, Ca silicate, and rice hull treatments were not significantly higher than those from the control.

The dextrin treatment gave the lowest forage yields in all four harvests. These low yields could have been due primarily to N immobilization considering the high rate of soluble sugar added to the soil. As for the forage, root weights were higher than the S. humilis, Ca silicate, and rice hull treatments than from the control. However, the yield differences were not statistically significant.

Phosphorus concentrations.--Forage P concentrations in the first and second harvests were generally higher from the S. humilis, Ca silicate, and rice hull treatments than from the control (Table 57). In the third and fourth harvests, however, forage P concentrations were comparable and at times P concentrations in the treated plants were even lower than that from the control. Forage P concentrations in the first harvest from the dextrin treatment were very low (0.03%) indicating the possibility of P immobilization by microorganisms. The P concentrations from the dextrin treatment increased appreciably

Table 56.--Effect of organic matter and Si on forage yields from four pangolagrass harvests and root weights.

Treatments	Harvests				
	1	2	3	4	Root
	g/pot				
Control	0.7 a[1]	2.0 ab	4.1 a	2.9 ab	0.5
Dextrin, 10 T/ha	0.5 a	1.3 a	2.8 a	2.5 a	0.6
S. humilis					
5 T/ha	1.7 cd	4.4 cd	5.2 a	4.6 b	1.2
10 T/ha	1.4 b	2.6 abc	4.7 a	4.1 ab	0.9
Ca silicate					
0.47 T/ha Si	1.5 bc	3.3 bcd	4.7 a	4.1 ab	0.9
1.41 T/ha Si	2.2 a	2.4 abc	3.5 a	3.4 ab	0.7
Rice hull					
0.47 T/ha Si	1.8 d	5.2 d	5.2 a	4.5 ab	1.4
1.41 T/ha Si	1.8 d	3.9 bcd	5.1 a	4.0 ab	0.9

[1] Values followed by the same lower case letter within each column are not significantly different at 0.05 probability level.

Table 57.--Effect of organic matter and Si on P concentrations in pangolagrass forage from four harvests.

	Harvests			
Treatments	1	2	3	4
	%			
Control	0.05	0.07	0.07	0.06
Dextrin, 10 T/ha	0.03	0.09	0.08	0.05
S. humilis				
5 T/ha	0.05	0.08	0.07	0.05
10 T/ha	0.06	0.10	0.08	0.06
Ca silicate				
0.47 T/ha Si	0.05	0.08	0.07	0.04
1.41 T/ha Si	0.07	0.07	0.08	0.07
Rice hull				
0.47 T/ha Si	0.07	0.07	0.06	0.04
1.41 T/ha Si	0.05	0.10	0.06	0.07

in the second and third harvests. Apparently, the plants were not benefited from this increase in P concentration because other factors were limiting growth. Differences in P concentrations were significant only at the first harvest (see appendix, Table 90).

Extractable soil P and soil pH.--Data in Table 58 show that Bray-Kurtz extractable soil P was significantly higher in the treated soils than in the control, especially in the Ca silicate and rice hull treatments. The magnitudes of increase in extractable P were not appreciable (7 ppm maximum); however, this may have been a significant amount since soil P was difficultly available. A portion of the extractable soil P increase from the *S. humilis* and rice hull treatments must have been derived from the decomposing plant materials. Soil pH was increased slightly by adding organic matter and Si to the soil.

The data obtained from this experiment indicated that there was only a temporary beneficial effect on pangolagrass from organic matter and Si applied to the pasture-surface soil. High rates of easily decomposable organic matter added to the soil were detrimental to plant growth. The beneficial effects of organic matter and Si on forage growth were nullified as soon as the grass roots became established and more efficient in extracting soil P. Addition of *S. humilis*, Ca silicate, and rice hulls increased forage yields possibly because of their effect in increasing the amount of relatively available P in the soil. The benefit from the added plant materials could have been due also to their N content especially with *S. humilis*. In the tropics where rice hulls are abundant, this material could be used advantageously as a soil amendment, particularly on small parcels of land.

Table 58.--Effect of organic matter and Si on Bray-Kurtz extractable soil P in the pasture-surface soil and pH.

Treatments	Extractable P	pH
	ppm	
Control	17 a[1]	4.85
Dextrin, 10 T/ha	22 bc	5.00
S. humilis		
5 T/ha	20 b	5.00
10 T/ha	20 b	5.05
Ca silicate		
0.47 T/ha Si	23 c	5.25
1.41 T/ha Si	23 c	5.05
Rice hull		
0.47 T/ha Si	23 c	5.10
1.41 T/ha Si	24 c	5.10

[1] Values followed by the same lower case letter are not significantly different at 0.05 probability level.

SUMMARY AND CONCLUSIONS

Laboratory and greenhouse experiments were conducted to study the effects of soil amendments and P fertilization on forage crops and P fractions in virgin and pasture soils from a tropical rainforest area at Los Diamantes, Costa Rica. Surface and subsoils were used in the study.

The Los Diamantes sandy loam soils were formed from alluvial deposits of volcanic material and contained amorphous clay fractions. The average total elemental compositions were Al, 11.3, Fe, 2.7; Ca, 3.1, Mg, 1.8, K, 1.3, and Na, 2.5%. The average total concentrations of Mn, Zn, and Cu in the soils were 733, 824, and 200 ppm, respectively. Organic matter concentrations in the surface soils were relatively high (virgin, 8.2%, pasture, 10.3%) and were twice those in the subsoils. The surface soils had an average of 0.44% N while the subsoils had 0.25%. The soil pH varied from 5.8 to 6.1.

The virgin soils had more exchangeable cations than the pasture soils, especially K. The total soil P concentrations were relatively high; they ranged from 1761 to 2401 ppm. However, soil P as determined by various chemical extractants had markedly low availability. The virgin soils had more extractable P than the pasture soils and the surface soils had more extractable P than the subsoils. The organic form accounted for more P than any other, amounts varied from 37 to 50% of the total P. The amounts of soil organic P appeared to be correlated with organic matter contents. Soil Al-P ranged from 7.2

to 13.2%, Fe-P, 6.4 to 10.9%, Ca-P, 4.1 to 5.2%, and occluded P, 26.5 to 40.9% of the total. The subsoils contained larger proportions of their total P in the occluded form than the surface soils.

Results from a laboratory experiment showed that Los Diamantes soils had high capacities to retain P. The amounts of P retained varied from 928 to 1,715 ppm. The pasture soils retained more P than the virgin soils. Lime increased the capacity of the soils to retain P. This effect was more pronounced in the subsoils than in the surface soils.

The amounts of exchangeable Al were small (0.11 to 8.7 ppm), and in most cases were not measurable after lime was applied to the soils. The 1 N NH_4OAc (pH 4.8)-extractable Al was decreased by lime while the 0.1 N HCl-extractable Al was not affected. Soil pH after incubation increased directly with lime rates from 5.0 (unlimed) to 6.9 (10.68 T lime/ha). The Al extracted with 1 N NH_4OAc (pH 4.8) and 0.1 N HCl was significantly correlated with the P retained by the soils.

Lime did not change significantly the soil Al-P, Fe-P, and Ca-P fractions before P treatment. Most of the P retained by the soils was in the form of Al-P and a lesser amount as Fe-P. After P treatment, Al-P increased three- to four-fold, Fe-P increased two- to three-fold, and Ca-P increased slightly, only in the virgin subsoil.

The first greenhouse experiment was of a factorial design consisting of three lime rates (0, 5, and 10 T $CaCO_3$/ha), four P rates (0, 50, 100, and 150 kg P/ha), and four soils. After four pangolagrass forage harvests, the roots were removed and the soils were screened. The soils (with treatments maintained) were planted to pigeon pea. The plants were cut after 60 days. The soils were planted again to pangolagrass after they were screened.

Results from the first pangolagrass planting showed that forage yields were higher from the virgin soils than from the pasture soils, and the yields from the surface soils were higher than from the subsoils. When P was not applied, plant growth in the subsoils was very limited for all harvests. The application of P in the subsoils resulted in an appreciable plant growth response, and in some cases, forage yields were almost comparable to yields from the surface soils.

In contrast to the subsoils, plant growth in the unfertilized surface soils improved markedly with time. Fourth harvest yields from the P_0 and P_1 treatments were approximately the same. Increased fixation of applied P with time may have accounted for part of the limited yield difference. However, the grass probably absorbed increasing amounts of P from the surface soils as root development proceeded.

Forage yields were significantly increased by applied P, and were significantly reduced by lime applications. There were no significant lime x P interaction effects on yield. Similar effects of P and lime on root weights were obtained. Forage Mn concentrations in the limed soils were markedly decreased. Micronutrient applications to the soils did not alleviate the depressing effect of lime on plant growth. The forage and root P concentrations were relatively low and in most cases were less than 0.10%. Forage P concentrations were increased by P applications. Lime did not affect the P concentrations of forage or roots. Phosphorus recoveries from the fertilizer varied from 7.1 to 24.4% of the applied P.

After a 7-month period, soil Al-P and Ca-P were increased by lime and fertilizer. However, Ca-P was not affected as markedly as Al-P. Lime slightly decreased the amount of Fe-P formed with P fertilization. Organic P was appreciably lower after the experiment was conducted than at the beginning. The magnitudes of decrease after 7 months were high (123 to 355 ppm) and were considered unrealistic. These high values were probably caused by the reduced resistance of microbiologically altered organic matter to hydrolysis by concentrated HCl pretreatment during analysis.

Pigeon pea forage yields from the surface soils were significantly higher than from the subsoils. Significant yield increases were obtained with P applications. In contrast to pangolagrass, pigeon pea growth was not suppressed by lime. At the P_2 and P_3 treatments, lime appeared to be beneficial to the growth of pigeon pea.

Lime appreciably decreased the Mn concentrations in pigeon pea while Zn and Cu concentrations were not affected. Although Mn concentrations in pigeon pea and pangolagrass were similarly affected by lime, pigeon pea forage yields were not adversely affected by lime as were the grass yields. This was possibly because of the lower requirement of pigeon pea for Mn as compared with pangolagrass. Average Mn concentrations in pigeon pea were only one-fourth those in pangolagrass. Phosphorus concentrations in pigeon pea forage were relatively low; values obtained were similar to those in pangolagrass.

In the second pangolagrass planting, forage yields and P concentrations were affected by lime and fertilizer P in a manner similar to those from the first planting. The yield response to P fertilizer was significant which indicated that the P applied 12 months before was relatively available to plants.

The second greenhouse experiment with pasture-surface soil was of a factorial design consisting of two lime rates (0 and 5 T $CaCO_3$/ha), and seven P rates (0 to 900 kg/ha). Results showed that for the limed and unlimed soils, forage yield responses to P fertilizer were described by quadratic equations. Forage yields from the limed soil were significantly lower than from the unlimed soil. The levels of applied P needed for maximum yields were high: unlimed soil, 820 and limed soil, 590 kg/ha.

Forage P concentration from the unlimed soil at which maximum yield was obtained was 0.09%. This concentration was much lower than those obtained from field experiments by other workers. Variations in the method of forage sampling in addition to soil and environmental variations probably contributed to differences in forage P concentrations obtained in this study and those previously reported. Percent P recoveries by the forage from the fertilizer varied from 3.4 to 11.6% depending on the lime and P levels. The highest percent recovery was obtained from the 300 kg P/ha application. Percent P recoveries from the limed soil were lower than from the unlimed soil.

Forage Mn and Cu concentrations were not significantly affected by P even at the high rates applied. Lime markedly decreased Mn concentrations in the forage. Foliar spraying with Mn did not alleviate the depressing effect of lime on plant growth, although Mn concentrations in the sprayed plants were markedly increased, especially in those from the limed soil.

Most of the fertilizer P was extracted from the soil as Al-P and relatively small percentages as Fe-P and Ca-P. Lime enhanced the formation of Al-P from fertilizer P, especially at high P rates. Lime did not significantly affect Fe-P and Ca-P. The P applied to the unlimed soil was less soluble than that applied to the limed soil. Water-soluble P was negligible for both lime treatments even at the high P rates.

In the third greenhouse experiment, the pasture-surface soil was mixed with five lime materials of different $CaCO_3$:$MgCO_3$ ratios. Triple superphosphate at rates of 0 and 150 kg P/ha were applied at each lime rate. Results showed that pangolagrass forage yields from the limed soil were generally lower than those from the unlimed soil. However, yield differences were not significant. Forage Mn concentrations were markedly reduced by all lime treatments.

Results from the fourth greenhouse experiment showed that fritted micronutrients (FTE-503), applied to the pasture-surface soil at rates 0 to 90 kg/ha, did not affect pangolagrass forage yields from the limed soils. The lime x micronutrient interaction was not significant. The Mn and Zn concentrations in the forage were increased only at the first harvest from the unlimed soil. Forage Mn concentrations were markedly decreased by lime applications. In the fourth harvest, however, forage Mn concentrations from the 5 T lime/ha treatment were relatively high and should have been adequate to meet the Mn requirement of the grass.

The Mn chelate and $MnSO_4$ treatments did not increase the yields of the grass in the limed soils. Forage Mn concentrations from the 5 T/ha lime treatment were high (133 to 257 ppm). In the 10 T/ha lime treatment, Mn concentrations remained consistently low. Forage Fe concentrations were not affected by high rates of applied Mn.

In the fifth greenhouse experiment, the pasture-surface soil was mixed with rice hulls, Ca silicate, S. humilis, and dextrin. Pangolagrass was temporarily benefited from the addition of plant organic matter and Si to the soil. The high rate of easily decomposable organic matter (dextrin) was detrimental to plant growth, probably because of N and P immobilization. Forage P concentrations were increased by the S. humilis, Ca silicate, and rice hull treatments only in the first and second harvests. In addition, Bray-Kurtz extractable P was significantly higher in the treated soils than in the control.

The following conclusions appear to be justified from the results of this study.

(a) Phosphorus fertilizer application was necessary to obtain satisfactory plant growth, especially in the subsoils, regardless of the high total P contents (1,761 to 2,401 ppm). A relatively high P rate (820 kg/ha in the unlimed soil) was needed to obtain the maximum pangolagrass forage yield. The average P concentration even at this P rate, however, was relatively low (0.09%). The surface soil P was much more available to the plants than that in the subsoils which discounted an earlier speculation that the subsoil may have been an important source of P on newly cleared land.

(b) The lime x P interaction effects on pangolagrass forage yields, root weights, and forage P concentrations was not statistically significant. Lime was detrimental to pangolagrass growth. The theory that lime increases P availability in acid soils probably was not evaluated. Lime may have increased the availability of P but it was not beneficial to the grass because of nutritional imbalances created. However, pigeon pea seemed to be benefited from lime application, but only where P was applied at 100 and 150 kg/ha rates.

(c) The detrimental effect of lime on pangolagrass probably was not caused by deterioration of soil structure because the soil was sandy loam. Moreover, it was observed that the roots from the limed soils were not injured or impeded in development as a result of deteriorated soil physical properties.

(d) The relatively high P retention capacities of the soils (988 to 1,715) suggested that P fertilizers should be applied banded and not broadcast.

(e) Lime increased the P retention capacities of the soils possibly because of the Al hydroxides produced which had high surface activity for P sorption. In general, the activity of Fe in soils is much less than that of Al. This may explain why more of the P applied was in the Al-P form than in Fe-P.

(f) As almost all of the applied P was in Al-P and pangolagrass responded to the applied P, the Al-P formed in the soil from the fertilizer was probably the primary source of P for the plants. Furthermore, since lime enhanced the formation of Al-P from the fertilizer, pangolagrass forage growth should have been benefited if it had not been for the lime induced nutritional imbalance.

(g) Lime did not affect the soil P fractions. However, there is a need for a better method than those presently available for determining organic P. A precise measure of the rate of P mineralization would be beneficial.

(h) The differential response of pigeon pea and pangolagrass to lime applications in the soil was probably caused by their differences in nutrient requirements or capacity to absorb nutrients. The depressed pangolagrass growth in the limed soils was not caused by deficiencies of Mg, K, Zn, Cu, and Fe.

(i) Although Mn concentrations in the grass forage were markedly decreased by lime, high rates of Mn (maximum, 220 kg/ha), applied to the soil and as a foliar spray, did not alleviate the detrimental effect of lime on pangolagrass growth. Therefore, Mn was probably not the cause of low grass forage yields from the limed soils.

(j) High rates of Mn applied to the soil did not affect Fe concentrations in the grass forage.

(k) Calcium silicate, *S. humilis*, and rice hulls increased pangolagrass forage yields and P concentrations above those from the control. This beneficial effect was probably caused by an increase in soil P availability. The increased P availability may have resulted from the complexing effect of $Si(OH)_4$ from these amendments on Al and Fe. In the tropics where rice hulls are abundant and often burned, they could be used advantageously as an amendment for soils especially for small parcels of land.

(l) The cause of depressed pangolagrass growth in the limed soils should be further investigated to include a wide range of plant species or varieties because it may occur widely in soils of the tropics. The investigation should consider the effects of lime on B and Mo availability to plants. The precipitation of Al hydroxides on plant root surfaces, thus blocking possible nutrient absorption sites, merits some attention.

APPENDIX

Table 59.--Effect of lime and P levels on forage yields from four pangolagrass harvests.

Lime levels (T/ha)	P levels (kg/ha)	Harvests							
		1	2	3	4	1	2	3	4
		g/pot							
		Virgin surface				Virgin subsoil			
0	0	3.20[1]	4.80	9.35	10.95	0.17	0.03	0.15	0.58
	50	5.44	6.69	8.60	11.13	5.21	3.09	4.25	3.38
	100	8.85	10.16	12.03	15.60	10.84	4.67	5.70	8.70
	150	7.46	10.56	14.53	12.68	11.64	9.12	10.95	8.80
	Avg.	6.24	8.05	11.13	12.60	6.96	4.24	5.26	5.36
5	0	0.38	1.68	2.73	2.88	0.06	0.04	0.13	1.24
	50	4.70	6.74	10.90	9.70	1.76	2.59	3.46	6.19
	100	2.26	7.34	8.65	11.05	2.43	3.87	7.70	7.88
	150	4.81	8.85	9.53	10.98	3.15	4.61	9.73	7.03
	Avg.	3.04	6.15	7.95	8.65	1.85	1.11	5.25	5.58
10	0	0.36	0.92	1.14	2.94	0.17	0.08	0.68	2.25
	50	1.23	2.16	2.26	3.28	0.45	0.53	1.47	1.74
	100	1.73	2.50	3.68	7.20	1.79	3.13	6.55	8.63
	150	1.33	3.70	8.38	14.70	1.17	4.03	7.00	8.95
	Avg.	1.16	2.32	3.86	7.03	0.89	1.94	3.97	5.39

Table 59.--Continued

Lime levels (T/ha)	P levels kg/ha	Harvests 1	2	3	4	1	2	3	4
		g/pot							
		Pasture surface				Pasture subsoil			
0	0	3.28	5.54	7.43	6.68	0.15	0.11	0.38	0.60
	50	5.21	7.47	8.73	6.10	2.48	2.27	3.44	5.05
	100	3.89	8.43	8.98	7.45	6.55	4.00	6.05	5.58
	150	13.30	8.82	8.23	9.75	5.79	6.88	5.40	4.88
	Avg.	6.24	7.57	8.34	7.49	3.74	3.31	3.82	4.02
5	0	1.15	1.55	5.58	6.15	0.09	0.04	0.05	0.11
	50	2.11	3.94	6.90	8.13	0.67	0.55	0.66	0.85
	100	6.03	6.73	6.78	10.30	2.83	2.79	7.03	6.50
	150	8.84	9.51	9.15	6.63	1.66	2.93	4.70	5.29
	Avg.	4.53	5.43	7.10	7.80	1.31	1.58	3.11	3.19
10	0	0.19	0.35	0.77	1.07	0.15	0.03	0.07	0.34
	50	0.79	1.44	4.94	6.83	0.21	0.57	2.01	1.85
	100	1.06	3.12	7.50	10.70	0.87	1.40	2.92	6.24
	150	1.24	4.56	5.28	5.78	0.53	1.22	1.05	2.04
	Avg.	0.82	2.37	4.62	6.09	0.44	0.80	1.51	2.62

[1] Average of four replications.

Table 60.--Effect of lime and P levels on soil pH.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
0	0	5.32[1]	4.89	5.08	5.10
	50	5.33	5.25	5.16	5.36
	100	5.73	5.60	5.28	5.59
	150	5.63	5.75	5.46	5.64
	Avg.	5.50	5.37	5.24	5.42
5	0	5.48	5.71	5.48	5.94
	50	5.80	6.18	5.68	6.05
	100	5.95	6.44	5.78	6.40
	150	6.05	6.56	5.86	6.36
	Avg.	5.84	6.22	5.70	6.19
10	0	6.16	6.64	5.94	6.48
	50	6.28	6.63	6.08	6.61
	100	6.31	7.01	6.24	6.68
	150	6.55	6.95	6.19	6.66
	Avg.	6.33	6.81	6.11	6.61

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[1] Average of four replications.

Table 61.—Effect of lime and P levels on the P concentrations in four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Harvests							
		1	2	3	4	1	2	3	4
		%							
		Virgin surface				Virgin subsoil			
0	0	0.09[1]	0.05	0.09	0.09	0.03	0.02	0.03	0.03
	50	0.10	0.06	0.08	0.10	0.06	0.05	0.04	0.07
	100	0.12	0.06	0.08	0.11	0.08	0.04	0.05	0.09
	150	0.12	0.08	0.07	0.11	0.11	0.06	0.05	0.08
	Avg.	0.11	0.06	0.08	0.10	0.07	0.04	0.04	0.07
5	0	0.08	0.06	0.07	0.07	0.06	0.01	0.03	0.05
	50	0.10	0.06	0.09	0.09	0.07	0.05	0.07	0.08
	100	0.13	0.07	0.08	0.10	0.08	0.06	0.06	0.08
	150	0.12	0.07	0.08	0.10	0.10	0.08	0.06	0.08
	Avg.	0.11	0.07	0.08	0.09	0.08	0.05	0.05	0.07
10	0	0.10	0.07	0.08	0.09	0.03	0.03	0.06	0.06
	50	0.12	0.07	0.07	0.07	0.04	0.07	0.04	0.07
	100	0.12	0.08	0.10	0.09	0.07	0.08	0.08	0.09
	150	0.13	0.09	0.07	0.11	0.10	0.06	0.05	0.07
	Avg.	0.12	0.08	0.08	0.09	0.05	0.06	0.06	0.07

Table 61.--Continued

Lime levels (T/ha)	P levels (kg/ha)	Harvests 1	2	3	4	1	2	3	4
		----	----	----	----	%	----	----	----
		Pasture surface				Pasture subsoil			
0	0	0.08	0.06	0.06	0.04	0.02	0.03	0.05	0.04
	50	0.08	0.07	0.06	0.08	0.06	0.04	0.05	0.07
	100	0.14	0.07	0.07	0.09	0.07	0.05	0.05	0.08
	150	0.08	0.06	0.07	0.09	0.09	0.05	0.04	0.07
	Avg.	0.09	0.07	0.06	0.08	0.06	0.04	0.05	0.06
5	0	0.06	0.06	0.08	0.08	0.04	0.02	0.05	0.02
	50	0.08	0.07	0.08	0.10	0.06	0.04	0.04	0.07
	100	0.09	0.06	0.08	0.09	0.06	0.07	0.06	0.07
	150	0.10	0.07	0.07	0.08	0.09	0.06	0.05	0.07
	Avg.	0.08	0.06	0.08	0.08	0.06	0.05	0.05	0.06
10	0	0.05	0.04	0.05	0.07	0.04	0.03	0.04	0.05
	50	0.06	0.07	0.07	0.07	0.04	0.04	0.04	0.04
	100	0.11	0.08	0.10	0.10	0.06	0.06	0.06	0.07
	150	0.13	0.08	0.06	0.06	0.07	0.07	0.04	0.07
	Avg.	0.09	0.07	0.07	0.07	0.05	0.05	0.05	0.06

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[1] Average of four replications.

Table 62.--Effect of lime and P levels on the P concentrations in pangolagrass roots after four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
		%			
0	0	0.05[1]	0.04	0.06	0.03
	50	0.05	0.04	0.06	0.05
	100	0.07	0.05	0.07	0.04
	150	0.07	0.04	0.09	0.03
	Avg.	0.06	0.04	0.07	0.04
5	0	0.04	0.03	0.05	0.03
	50	0.06	0.04	0.06	0.03
	100	0.06	0.04	0.06	0.04
	150	0.05	0.05	0.06	0.04
	Avg.	0.05	0.04	0.06	0.04
10	0	0.05	0.04	0.05	0.04
	50	0.04	0.04	0.05	0.03
	100	0.06	0.06	0.05	0.05
	150	0.07	0.06	0.05	0.04
	Avg.	0.05	0.05	0.05	0.04

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[1] Average of four replications.

Table 63.--Analysis of variance for the data shown in Tables 61 and 62.

Source	df	F Forage	 Root
Rep	3	6.90^{**}	2.94^{*}
Soil	3	76.00^{**}	30.38^{**}
Lime	2	0.33	2.81
Phosphorus	3	47.80^{**}	0.94
S x L	6	0.47	3.25^{**}
S x P	9	1.80	0.81
L x P	6	1.73	1.13
S x L x P	18	1.47	1.44
Error	141		
Total	191		

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*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 64.--Effect of lime and P levels on the total P contents of four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
		mg P/pot			
0	0	19.93[1]	0.52	14.42	0.58
	50	28.18	8.34	18.83	7.66
	100	43.12	17.58	23.68	13.24
	150	41.16	29.68	29.09	14.72
5	0	5.43	1.11	10.63	0.11
	50	26.42	10.45	18.61	1.44
	100	25.57	15.93	22.37	13.42
	150	30.62	19.87	26.24	10.90
10	0	5.29	3.24	1.46	0.13
	50	6.34	2.50	10.84	3.15
	100	14.96	17.34	22.20	8.81
	150	28.94	14.16	11.64	3.46

[1] Average of four replications.

Table 65.--Effect of lime and P levels on the total P concentrations in pangolagrass roots after four forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
		mg P/pot			
0	0	2.13[1]	0.37	3.39	0.34
	50	2.24	1.94	2.36	2.87
	100	5.04	3.24	5.30	2.59
	150	6.15	2.88	13.82	2.47
5	0	0.67	0.31	1.62	0.14
	50	2.76	1.57	2.64	0.50
	100	3.35	2.71	4.64	2.45
	150	2.16	3.07	4.21	3.68
10	0	0.54	0.81	0.32	0.12
	50	0.66	0.57	1.39	0.48
	100	0.97	2.95	2.27	1.18
	150	3.04	4.97	2.13	0.97

[1] Average of four replications.

Table 66.--Analysis of variance for the data shown in Tables 16, 17, and 65.

		F	
Source	df	Forage	Root
Rep	3	1.27	3.72*
Soil	3	4.73**	9.29**
Lime	2	29.50**	16.49**
Phosphorus	3	53.41**	22.65**
S x L	6	3.85**	4.08**
S x P	9	1.71	1.20
L x P	6	1.31	1.72
S x L x P	18	1.42	2.42**
Error	141		
Total	191		

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 67.--Calcium and Mg concentrations in the first and fourth pangolagrass forage harvests as affected by lime and P levels.

Lime levels (T/ha)	P levels (kg/ha)	Harvests							
		1	4	1	4	1	4	1	4
		--- % Ca ----		--- % Mg ----		--- % Ca ----		--- % Mg ----	
		Virgin surface				Virgin subsoil			
0	0	0.36[1]	0.40	0.33	0.47	0.95	0.97	0.57	0.34
	50	0.31	0.49	0.34	0.56	0.28	0.50	0.21	0.34
	100	0.34	0.44	0.46	0.53	0.22	0.37	0.19	0.29
	150	0.35	0.58	0.44	0.60	0.22	0.44	0.18	0.42
	Avg.	0.34	0.47	0.39	0.54	0.42	0.57	0.28	0.35
5	0	0.69	0.47	0.68	0.40	1.43	1.31	0.52	0.43
	50	0.44	0.51	0.47	0.47	0.64	0.64	0.50	0.36
	100	0.40	0.42	0.48	0.55	0.47	0.59	0.46	0.39
	150	0.37	0.45	0.44	0.55	0.36	0.54	0.34	0.45
	Avg.	0.47	0.46	0.51	0.49	0.72	0.77	0.46	0.41
10	0	0.70	0.51	0.62	0.43	1.31	1.62	0.48	0.43
	50	0.52	0.56	0.46	0.37	0.57	0.68	0.58	0.34
	100	0.51	0.41	0.49	0.40	1.49	0.47	0.64	0.34
	150	0.54	0.49	0.48	0.48	1.03	0.51	0.49	0.40
	Avg.	0.57	0.49	0.51	0.42	1.20	0.82	0.55	0.38

Table 67.--Continued

Lime levels (T/ha)	P levels (kg/ha)	Harvests 1	4	1	4	1	4	1	4
		--- % Ca ----		--- % Mg ----		--- % Ca ----		--- % Mg ----	
		Pasture surface				Pasture subsoil			
0	0	0.23	0.39	0.29	0.44	0.63	0.74	0.45	0.34
	50	0.24	0.47	0.32	0.62	0.34	0.49	0.31	0.31
	100	0.27	0.50	0.31	0.62	0.26	0.52	0.23	0.40
	150	0.21	0.52	0.29	0.57	0.37	0.49	0.32	0.42
	Avg.	0.23	0.47	0.30	0.56	0.40	0.56	0.33	0.37
5	0	0.31	0.37	0.51	0.37	1.48	1.96	0.44	0.38
	50	0.43	0.56	0.46	0.58	0.98	0.70	0.52	0.34
	100	0.42	0.58	0.42	0.51	0.48	0.53	0.37	0.33
	150	0.49	0.69	0.31	0.58	0.54	0.59	0.37	0.34
	Avg.	0.41	0.55	0.42	0.51	0.87	0.94	0.42	0.35
10	0	0.66	0.92	0.56	0.36	0.84	2.84	0.32	0.32
	50	0.75	0.63	0.61	0.44	1.28	1.17	0.51	0.31
	100	0.63	0.50	0.52	0.46	0.84	0.74	0.32	0.46
	150	0.53	0.75	0.47	0.51	0.92	0.77	0.37	0.41
	Avg.	0.64	0.70	0.54	0.44	0.97	1.38	0.38	0.37

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[1] Average of four replications.

Table 68.--Effect of lime and P levels on the K contents of four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Harvests 1	2	3	4	1	2	3	4
		%							
		Virgin surface				Virgin subsoil			
0	0	2.61[1]	2.64	2.68	2.46	1.27	2.06	2.01	2.12
	50	2.93	2.66	2.58	2.22	2.30	2.45	2.15	2.45
	100	2.96	2.66	2.10	1.09	2.70	2.43	2.00	2.44
	150	2.99	2.71	1.85	0.99	2.86	2.19	1.52	1.62
	Avg.	2.87	2.67	2.30	1.69	2.28	2.28	1.92	2.16
5	0	3.35	2.73	2.57	2.79	2.39	2.08	1.73	2.45
	50	2.90	2.53	2.24	2.13	2.36	2.35	2.20	2.40
	100	3.20	2.77	2.50	2.42	2.63	2.46	1.99	2.48
	150	2.97	2.61	2.50	2.13	2.52	2.55	1.94	2.40
	Avg.	3.10	2.66	2.45	2.37	2.47	2.36	1.96	2.43
10	0	3.13	2.54	2.63	3.03	2.36	1.79	1.98	2.01
	50	3.18	2.80	2.61	2.79	1.98	2.27	1.99	2.42
	100	2.94	2.58	2.76	3.06	2.50	2.43	2.05	2.35
	150	2.98	2.65	2.45	2.57	2.81	2.43	2.11	1.98
	Avg.	3.08	2.64	2.61	2.74	2.41	2.23	2.03	2.19

Table 68.--Continued

Lime levels	P levels	Harvests							
		1	2	3	4	1	2	3	4
(T/ha)	(kg/ha)	%							
		Pasture surface				Pasture subsoil			
0	0	2.66	2.51	1.98	1.77	1.25	1.56	1.86	1.87
	50	2.69	2.38	1.41	1.39	2.45	2.29	2.05	2.56
	100	3.08	2.34	1.54	1.29	2.26	2.00	1.71	1.94
	150	2.22	1.56	0.83	0.89	2.60	2.12	1.79	1.90
	Avg.	2.66	2.20	1.44	1.33	2.14	1.99	1.85	2.07
5	0	2.60	2.93	2.57	2.78	2.06	1.68	2.12	2.58
	50	3.00	2.71	1.91	1.98	2.13	2.02	1.87	2.18
	100	2.81	2.01	1.81	1.54	2.40	2.41	1.91	1.60
	150	2.52	1.74	1.42	1.28	2.81	2.33	1.76	1.51
	Avg.	2.73	2.35	1.93	1.89	2.35	2.11	1.92	1.97
10	0	2.58	2.25	2.01	2.45	1.98	1.59	1.58	3.55
	50	2.37	2.98	2.46	2.28	2.23	2.12	2.20	2.36
	100	3.21	2.59	2.58	2.04	2.38	2.43	2.27	3.03
	150	3.25	2.69	2.27	2.27	2.70	2.23	1.97	2.54
	Avg.	2.85	2.63	2.33	2.26	2.32	2.09	2.00	2.87

[1] Average of four replications.

Table 69.--Effect of lime and P levels on the K contents of pangolagrass roots after four forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin soil		Pasture soil	
		Surface	Subsoil	Surface	Subsoil
		%			
0	0	0.59[1]	0.35	0.40	0.30
	50	0.47	0.41	0.32	0.31
	100	0.21	0.44	0.34	0.30
	150	0.28	0.38	0.20	0.36
	Avg	0.38	0.40	0.31	0.32
5	0	0.61	0.37	0.52	0.36
	50	0.40	0.45	0.41	0.36
	100	0.41	0.48	0.30	0.35
	150	0.40	0.44	0.28	0.32
	Avg.	0.45	0.41	0.38	0.35
10	0	0.57	0.39	0.48	0.38
	50	0.62	0.45	0.47	0.30
	100	0.77	0.43	0.49	0.39
	150	0.62	0.36	0.51	0.41
	Avg.	0.64	0.41	0.49	0.37

[1] Average of four replications.

Table 70.--Effect of lime and P levels on the K contents of four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Harvests							
		1	2	3	4	1	2	3	4
		mg/pot							
		Virgin surface				Virgin subsoil			
0	0	68.4[1]	184.9	233.1	260.6	1.7	1.7	2.6	15.3
	50	158.0	204.4	219.2	250.3	124.6	79.3	88.9	82.8
	100	258.3	322.2	290.5	168.3	273.6	117.3	107.3	207.5
	150	218.3	265.8	230.5	121.1	314.1	187.5	171.9	141.6
	Avg.	175.7	244.3	243.3	200.1	178.5	96.5	92.7	111.8
5	0	5.5	73.6	72.2	83.0	1.5	2.8	2.9	35.4
	50	127.1	174.4	273.1	160.9	42.2	58.9	71.9	156.2
	100	71.1	259.5	233.4	263.5	63.3	91.2	143.3	188.5
	150	140.6	282.2	235.7	221.6	82.4	104.6	186.4	161.5
	Avg.	86.1	197.4	203.6	182.3	47.3	64.4	100.4	135.4
10	0	11.4	35.8	31.1	90.7	3.2	52.8	19.5	59.6
	50	39.4	63.6	57.7	91.7	9.9	24.2	31.7	45.0
	100	49.7	97.9	101.7	214.7	39.8	113.3	123.8	238.5
	150	39.2	231.2	201.1	347.5	31.8	99.7	145.8	164.0
	Avg.	34.9	107.1	98.1	186.2	21.2	72.5	80.2	126.7

Table 70.--Continued

Lime levels (T/ha)	P levels kg/ha	Harvests 1	2	3	4	1	2	3	4
		-----------------	-----------------	-----------------	mg/pot	-----------------	-----------------	-----------------	-----------------
		Pasture surface				Pasture subsoil			
0	0	87.1	133.5	134.9	104.1	1.9	1.8	7.3	13.0
	50	135.1	166.4	123.0	73.7	61.0	51.5	67.7	127.2
	100	120.6	190.7	142.0	91.7	142.7	79.5	99.5	104.0
	150	290.1	135.5	68.0	87.0	149.4	132.2	95.5	86.3
	Avg.	158.2	156.5	117.0	89.1	88.7	66.2	67.5	82.6
5	0	27.6	45.5	141.8	164.6	3.7	3.2	1.0	2.5
	50	60.2	107.7	136.8	134.7	14.7	12.5	13.5	20.9
	100	147.5	119.3	99.0	162.3	65.3	66.1	129.9	80.3
	150	213.0	164.3	120.7	80.0	44.4	64.2	67.8	91.8
	Avg.	112.1	109.2	124.5	135.4	32.0	36.5	53.0	48.9
10	0	5.3	8.0	18.1	29.9	3.0	0.5	1.1	10.8
	50	17.9	42.6	127.6	141.5	4.5	11.9	44.6	42.6
	100	33.3	80.4	170.5	204.9	21.3	37.7	65.8	152.9
	150	39.2	129.1	119.7	131.0	14.9	28.4	20.8	57.4
	Avg.	23.9	65.0	105.0	126.8	10.9	19.6	33.1	65.9

[1] Average of four replications.

Table 71.--Effect of lime and P levels on the K contents of pangolagrass roots after four forage harvests.

Lime levels	P levels	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
(T/ha)	(kg/ha)	mg/pot			
0	0	24.0[1]	3.3	20.8	3.1
	50	22.4	22.3	16.9	17.3
	100	15.3	33.0	22.8	22.1
	150	22.0	29.3	28.6	27.0
	Avg.	20.9	22.0	22.3	17.4
5	0	11.0	3.5	16.6	1.4
	50	14.0	19.6	16.6	6.1
	100	21.4	27.4	19.4	19.8
	150	15.1	26.2	19.4	17.3
	Avg.	15.3	19.2	18.0	11.1
10	0	6.5	6.6	4.6	1.3
	50	10.9	8.3	13.7	5.2
	100	13.9	17.8	14.2	10.1
	150	41.9	29.8	22.8	9.7
	Avg.	14.8	15.6	13.8	6.6

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[1] Average of four replications.

Table 72.--Effect of lime and P levels on the Mn, Zn, and Cu concentrations in pangolagrass forage.[1]

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface Mn	Virgin surface Zn	Virgin surface Cu	Virgin subsoil Mn	Virgin subsoil Zn	Virgin subsoil Cu
		ppm					
0	0	257[2]	49	31	52	127	57
	50	265	43	26	177	36	27
	100	199	43	31	148	29	20
	150	187	39	28	58	33	28
	Avg.	227	44	29	119	56	33
5	0	76	42	26	30	274	130
	50	42	43	27	41	42	22
	100	46	44	24	25	41	24
	150	35	36	28	25	37	26
	Avg.	50	41	26	30	98	54
10	0	15	58	23	20	203	140
	50	14	52	32	21	35	19
	100	16	41	29	16	29	28
	150	10	39	27	31	44	27
	Avg.	14	48	28	22	78	54

Table 72.--Continued

Lime levels (T/ha)	P levels (kg/ha)	Pasture surface Mn	Pasture surface Zn	Pasture surface Cu	Pasture subsoil Mn	Pasture subsoil Zn	Pasture subsoil Cu
		ppm					
0	0	220	53	26	507	58	53
	50	209	43	26	187	50	29
	100	174	46	31	180	47	24
	150	194	49	32	111	40	19
	Avg.	199	48	29	246	48	31
5	0	134	48	30	8	112	115
	50	80	51	34	32	39	21
	100	65	38	36	32	29	28
	150	56	39	45	32	35	34
	Avg.	84	44	36	26	54	50
10	0	38	66	48	44	67	122
	50	31	46	34	15	36	34
	100	20	30	23	28	35	33
	150	20	49	28	32	32	38
	Avg.	27	48	33	30	42	57

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[1] Data for second harvest.

[2] Average of four replications.

Table 73.--Summary of F values from the analysis of variance for data shown in Tables 23, 24, and 72.

		F		
Source	df	Mn	Zn	Cu
Rep	3	0.99	1.05	0.55
Soil	3	32.43^{**}	10.40^{**}	7.79^{**}
Lime	2	810.96^{**}	1.49	5.30^{**}
Phosphorus	3	28.73^{**}	33.69^{**}	33.88^{**}
S x L	6	27.94^{**}	1.78	1.48
S x P	9	15.62^{**}	14.43^{**}	11.22^{**}
L x P	6	13.27^{**}	2.21^{*}	3.35^{**}
S x L x P	18	19.24^{**}	1.15	
Error	141			
Total	191			

[*] Significant at 0.05 probability level.

[**] Significant at 0.01 probability level.

Table 74.--Summary of F values from the analysis of variance for Soil P fractions data shown in Tables 25, 26, and 27.

		F				F
Source	df	Al-P	Fe-P	Ca-P	df	Organic P
Rep	3	0.55	1.17	1.05	3	0.18
Soil	3	2862.69**	247.83**	3.14*	3	257.97**
Lime	2	6.80**	13.01**	4.71**	2	1.18
Phosphorus	3	116.98**	43.53**	15.43**	1	2.32
S x L	6	11.84**	3.43**	2.45*	6	2.01
S x P	9	2.53**	1.80	1.02	3	1.13
L x P	6	6.14**	2.73*	1.76	2	2.85
S x L x P	18	4.90**	1.07	3.88**	6	2.31
Error	141				69	
Total	191				95	

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 75.--Effect of lime and P levels on pigeon pea forage yields and root weights following four pangolagrass forage harvests.

Lime levels	P levels	Virgin surface		Virgin subsoil		Pasture surface		Pasture subsoil	
		Top	Root	Top	Root	Top	Root	Top	Root
(T/ha)	(kg/ha)	g/pot							
0	0	4.0[1]	1.34	1.8	0.86	4.0	1.27	1.7	0.93
	50	5.0	1.27	3.0	1.15	3.2	1.48	2.2	1.31
	100	4.3	1.04	3.6	1.01	3.5	1.12	2.7	1.35
	150	4.9	1.09	3.3	1.06	4.4	1.32	2.9	1.39
	Avg.	4.5	1.18	2.9	1.02	3.8	1.30	2.4	1.24
5	0	1.9	0.62	2.5	0.80	3.0	1.11	1.8	0.77
	50	4.2	0.55	3.7	0.57	3.7	1.14	2.4	0.88
	100	4.7	0.58	3.4	1.02	4.3	1.26	3.5	1.41
	150	4.8	1.02	3.9	0.54	4.8	1.15	2.5	1.15
	Avg.	3.9	0.89	3.3	0.93	3.9	1.17	2.5	1.05
10	0	4.0	0.83	2.6	0.86	3.4	0.94	1.9	0.78
	50	2.1	0.50	2.9	0.87	3.5	0.97	2.4	1.26
	100	5.2	1.05	4.2	1.06	4.6	1.29	4.1	1.26
	150	4.8	1.02	4.1	1.15	4.0	1.03	4.1	1.08
	Avg.	4.0	0.85	3.4	0.98	3.9	1.17	3.1	1.13

[1] Average of four replications.

Table 76.--Analysis of variance for data shown in Tables 28, 29, and 73.

		Top		Root	
Source	df	MS	F	MS	F
Rep	3	3.32	5.27**	0.507	7.92**
Soil	3	20.70	32.86**	0.497	7.77**
Lime	2	0.93	1.48	0.715	11.17**
Phosphorus	3	19.73	31.32**	0.513	8.02**
S x L	6	1.56	2.48*	0.078	1.22
S x P	9	0.55	0.87	0.100	1.56
L x P	6	2.98	4.73**	0.208	3.25**
S x L x P	18	1.29	2.05**	0.057	0.89
Error	141	0.63		0.064	
Total	191				

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 77.--Effect of lime and P levels on the P, Ca, Mg, and K concentrations in pigeon pea forage following four pangolagrass forage harvests.

Lime Levels (T/ha)	P Levels (kg/ha)	Virgin surface P	Virgin surface Ca	Virgin surface Mg	Virgin surface K	Virgin subsoil P	Virgin subsoil Ca	Virgin subsoil Mg	Virgin subsoil K
		%							
0	0	0.09[1]	1.12	0.23	1.18	0.05	1.69	0.23	0.84
	50	0.09	0.88	0.32	0.76	0.07	1.09	0.18	1.15
	100	0.09	0.90	0.31	0.77	0.08	0.86	0.21	0.97
	150	0.09	0.89	0.33	0.70	0.08	0.95	0.23	0.73
5	0	0.07	2.01	0.26	2.60	0.05	1.52	0.18	0.92
	50	0.09	1.08	0.26	1.14	0.07	1.07	0.16	1.00
	100	0.10	1.00	0.27	0.93	0.08	1.02	0.16	1.07
	150	0.11	0.97	0.25	0.75	0.08	0.89	0.16	1.12
10	0	0.09	1.45	0.14	1.45	0.07	1.75	0.13	1.08
	50	0.10	1.88	0.21	1.42	0.07	1.62	0.12	1.17
	100	0.09	1.02	0.19	1.13	0.10	0.91	0.17	1.11
	150	0.13	1.14	0.26	0.89	0.09	0.91	0.16	0.96
	Avg.	0.09	1.19	0.25	1.01	0.07	1.19	0.17	1.01

Table 77.--Continued

Lime Level (T/ha)	P levels (kg/ha)	Pasture surface P	Pasture surface Ca	Pasture surface Mg	Pasture surface K	Pasture subsoil[1] P	Pasture subsoil[1] Ca	Pasture subsoil[1] Mg	Pasture subsoil[1] K
		%							
0	0	0.06	0.94	0.21	0.94	0.05	1.26	0.13	0.87
	50	0.05	0.97	0.21	0.94	0.04	1.09	0.15	0.80
	100	0.06	1.01	0.21	0.97	0.05	0.86	0.15	0.97
	150	0.06	0.76	0.19	0.81	0.05	0.89	0.15	0.84
5	0	0.04	1.31	0.16	1.09	0.04	1.77	0.15	0.79
	50	0.04	1.09	0.19	0.96	0.04	1.58	0.15	0.99
	100	0.05	0.92	0.19	1.03	0.05	1.58	0.11	0.90
	150	0.08	0.88	0.23	0.92	0.07	1.19	0.14	1.23
10	0	0.06	1.49	0.14	1.38	0.05	2.04	0.11	0.94
	50	0.07	1.28	0.18	1.40	0.05	1.66	0.12	1.00
	100	0.06	1.02	0.20	1.05	0.05	0.96	0.13	0.69
	150	0.08	1.15	0.16	1.27	0.07	1.01	0.10	1.20
	Avg.	0.06	1.06	0.19	1.06	0.05	1.32	0.14	0.93

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[1] Average of four replications.

Table 78.--Effect of lime and P levels on the P contents of pigeon pea forage following four pangolagrass forage harvests.

Lime levels	P levels	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
(T/ha)	(kg/ha)	mg/pot			
0	0	3.47[1]	1.05	2.21	0.74
	50	4.44	2.06	1.72	0.89
	100	3.66	2.75	1.92	1.26
	150	4.51	2.54	2.50	1.53
	Avg.	4.02	2.10	2.09	1.10
5	0	1.44	1.15	1.13	0.77
	50	3.58	2.71	1.64	1.11
	100	4.58	2.67	2.02	1.76
	150	5.12	3.18	3.69	1.72
	Avg.	3.68	2.43	2.12	1.34
10	0	3.46	1.77	1.86	1.06
	50	2.08	2.03	2.05	0.93
	100	4.70	4.08	2.87	2.09
	150	6.11	3.50	3.25	2.69
	Avg.	4.08	2.84	2.51	1.69

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[1] Average of four replications.

Table 79.--Micronutrient concentrations in pigeon pea forage as affected by lime and P levels following four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface Mn	Virgin surface Zn	Virgin surface Cu	Virgin subsoil Mn	Virgin subsoil Zn	Virgin subsoil Cu
		ppm					
0	0	71[1]	45	19	268	42	18
	50	49	43	18	108	43	21
	100	41	54	19	71	41	21
	150	50	32	17	84	44	21
	Avg.	53	43	18	133	43	20
5	0	50	48	18	55	47	20
	50	33	40	19	33	45	23
	100	28	39	20	33	42	20
	150	40	43	19	34	41	19
	Avg.	37	42	19	38	43	20
10	0	20	45	19	23	41	21
	50	23	46	20	23	44	24
	100	25	40	17	23	39	23
	150	25	41	20	28	43	25
	Avg.	23	43	19	24	42	23

Table 79.--Continued

Lime levels (T/ha)	P levels (kg/ha)	Pasture surface			Pasture subsoil		
		Mn	Zn	Cu	Mn	Zn	Cu
		ppm					
0	0	83	53	19	185	50	21
	50	60	48	20	105	38	20
	100	58	47	18	71	37	21
	150	50	45	17	68	42	18
	Avg.	63	48	18	107	42	20
5	0	41	50	21	80	41	14
	50	29	42	19	45	42	16
	100	29	45	19	13	43	18
	150	23	36	22	29	57	18
	Avg.	30	43	20	42	46	16
10	0	20	43	19	19	47	19
	50	19	45	21	19	42	15
	100	18	45	20	21	35	16
	150	16	50	20	15	53	16
	Avg.	18	46	20	19	44	16

[1] Average of four replications.

Table 80.--Effect of lime and P levels on pangolagrass forage yields and P concentrations following pigeon pea and four pangolagrass harvests.

Lime levels	P levels	Forage yield				Forage P			
		Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil	Virgin surface	Virgin subsoil	Pasture surface	Pastura subsoil
(T/ha)	(kg/ha)	g/pot				%			
0	0	3.1[1]	0.9	2.1	1.8	0.08	0.06	0.05	0.04
	50	2.7	1.7	2.9	1.5	0.08	0.07	0.04	0.04
	100	3.2	2.6	2.1	1.7	0.07	0.07	0.06	0.03
	150	3.1	3.0	3.3	2.2	0.08	0.08	0.06	0.06
	Avg.	3.0	2.1	2.6	1.8	0.08	0.07	0.05	0.04
5	0	1.2	0.9	1.6	1.1	0.05	0.06	0.04	0.03
	50	3.1	2.4	1.4	1.1	0.08	0.06	0.05	0.04
	100	2.9	2.4	2.5	1.2	0.08	0.06	0.03	0.05
	150	2.2	2.3	4.4	1.2	0.09	0.07	0.05	0.06
	Avg.	2.4	2.0	2.5	1.2	0.08	0.06	0.04	0.04
10	0	0.9	1.1	1.3	0.7	0.10	0.07	0.04	0.04
	50	1.5	0.8	1.7	1.2	0.08	0.07	0.06	0.05
	100	1.0	2.2	2.2	1.4	0.07	0.08	0.06	0.07
	150	2.2	2.3	1.3	1.1	0.08	0.09	0.06	0.07
	Avg.	1.6	1.6	2.2	1.1	0.08	0.08	0.06	0.06

[1] Average of three replications.

Table 81.--Analysis of variance for data shown in Table 80.

Source	df	Forage yield MS	Forage yield F	Forage P MS	Forage P F
Rep	2	7.59	9.73**	0.00005	0.24
Soil	3	7.17	9.19**	0.00823	39.19**
Lime	2	9.58	12.28**	0.00140	6.67**
Phosphorus	3	7.06	9.05**	0.00163	7.76**
S x L	6	0.73	0.94	0.00008	0.38
S x P	9	0.76	0.97	0.00017	0.81
L x P	6	0.34	0.44	0.00020	0.95
S x L x P	18	1.38	1.77*	0.00035	1.67*
Error	94	0.78		0.00021	
Total	143				

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 82.--Effect of lime and P levels on the P contents of pangolagrass forage following pigeon pea and four pangolagrass forage harvests.

Lime levels (T/ha)	P levels (kg/ha)	Virgin surface	Virgin subsoil	Pasture surface	Pasture subsoil
		mg/pot			
0	0	2.48[1]	0.54	1.05	0.72
	50	2.16	1.19	1.16	0.60
	100	2.24	1.82	1.26	0.51
	150	2.48	2.40	1.98	1.32
	Avg.	2.34	1.49	1.36	0.79
5	0	0.60	0.54	0.64	0.33
	50	2.48	1.44	0.70	0.44
	100	2.32	1.44	0.75	0.60
	150	1.98	1.61	2.20	0.72
	Avg.	1.85	1.26	1.07	0.52
10	0	0.90	0.77	0.52	0.28
	50	1.20	0.56	1.02	0.60
	100	0.70	1.76	1.32	0.98
	150	1.76	2.07	0.78	0.77
	Avg.	1.14	1.29	0.91	0.66

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[1] Average of three replications.

Table 83.--Micronutrient concentrations in pangolagrass forage as affected by lime and P levels following pigeon pea and four pangolagrass forage harvests.

Lime levels T/ha	P levels kg/ha	Virgin surface Mn	Virgin surface Zn	Virgin surface Cu	Virgin surface Fe	Virgin subsoil Mn	Virgin subsoil Zn	Virgin subsoil Cu	Virgin subsoil Fe
		ppm							
0	0	273[1]	32	53	37	775	29	24	39
	50	260	29	40	33	586	31	35	39
	100	190	25	33	40	603	30	30	47
	150	230	32	47	53	507	36	33	47
	Avg.	179	30	43	41	463	32	31	43
5	0	107	28	32	40	120	38	43	33
	50	53	30	40	30	56	34	38	39
	100	53	30	37	30	50	30	33	47
	150	41	34	43	38	53	31	43	47
	Avg.	48	31	38	35	52	33	40	41
10	0	21	36	31	27	16	29	33	37
	50	12	37	44	38	16	25	32	44
	100	13	49	47	30	10	24	40	43
	150	10	31	33	35	34	28	54	44
	Avg.	11	38	39	33	14	26	40	42

Table B3.--Continued

Lime levels (T/ha)	P levels (kg/ha)	Pasture surface					Pasture subsoil			
		Mn	Zn	Cu	Fe		Mn	Zn	Cu	Fe
						ppm				
0	0	340	37	45	39		1056	29	44	50
	50	283	46	43	33		733	23	23	43
	100	301	46	37	27		787	27	23	27
	150	220	42	50	40		715	30	35	31
	Avg.	215	43	44	35		617	27	32	38
5	0	104	34	27	30		135	25	25	43
	50	57	40	33	34		131	31	38	36
	100	47	33	33	43		64	31	50	28
	150	43	33	50	43		58	34	40	25
	Avg.	47	35	36	38		73	30	38	33
10	0	31	38	30	37		17	26	50	51
	50	11	34	50	50		13	21	37	37
	100	10	28	40	47		15	31	33	43
	150	10	22	28	40		11	30	29	53
	Avg.	12	31	37	44		10	30	37	46

[1] Average of three replications.

Table 84.--Effect of P levels in limed and unlimed pasture-surface soil on pangolagrass forage yields and P concentrations.

Lime levels (T/ha)	P levels (kg/ha)	Harvests 1	2	3	4	1	2	3	4
		------	g/pot	------		------	%	------	
		Forage Yields				P concentrations			
0	0	1.6[1]	3.1	2.7	2.6	0.05	0.06	0.05	0.04
	150	2.7	3.5	3.9	3.5	0.08	0.07	0.05	0.05
	300	3.4	4.3	3.7	5.7	0.10	0.08	0.09	0.07
	450	5.3	4.5	4.9	4.9	0.09	0.12	0.08	0.07
	600	2.9	4.2	3.5	4.9	0.10	0.10	0.09	0.08
	750	4.7	4.3	5.5	6.3	0.10	0.10	0.09	0.06
	900	4.6	3.5	4.9	6.6	0.13	0.12	0.11	0.12
	Avg.	3.6	3.9	4.1	4.9	0.09	0.09	0.08	0.07
5	0	1.8	3.3	2.4	2.1	0.07	0.07	0.04	0.03
	150	3.5	3.2	1.6	2.9	0.08	0.10	0.08	0.06
	300	3.3	3.3	3.1	4.3	0.08	0.14	0.13	0.08
	450	3.8	3.5	2.3	3.2	0.10	0.08	0.10	0.10
	600	3.4	4.8	2.8	3.9	0.13	0.12	0.10	0.10
	750	4.6	4.3	3.3	5.6	0.11	0.10	0.11	0.08
	900	3.8	3.2	1.2	3.1	0.12	0.11	0.09	0.11
	Avg.	3.5	2.6	2.4	3.6	0.09	0.10	0.09	0.08

[1] Average of four replications.

Table 85.--Analysis of variance for the micronutrient concentrations in pangolagrass forage shown in Table 43.[1]

		Mn		Zn		Cu	
Source	df	MS	F	MS	F	MS	F
Rep	3	1,824	1.19	86	1.51	155	0.69
Lime	1	811,207	28.47**	1,090	19.12**	865	3.83
Phosphorus	6	2,565	1.67	23	0.40	534	2.36
L x P	6	1,376	0.90	20	0.35	354	1.57
Error	39	1,535		57		226	
Total	55						

[1] Data from third harvest.

**Significant at 0.01 probability level.

Table 86.--Analysis of variance for data shown in Table 44.[1]

		Forage yields		Mn concentrations	
Source	df	MS	F	MS	F
Main plot					
Rep	1	1.61	2.01	945	0.73
Manganese	1	7.65	9.56	278,616	213.99^{*}
Error (a)	1	0.80		1,302	
Subplot					
Lime	1	23.99	8.33^{**}	1,067,016	255.45^{**}
Phosphorus	6	11.48	3.99^{**}	18,816	4.50^{**}
L x P	6	2.20	0.76	6,845	1.63
Mn x L	1	3.47	1.20	2,188	0.52
Mn x P	6	2.35	0.82	3,529	0.84
Mn x L x P	6	6.98	2.42	3,192	0.76
Error (b)	26	2.88		4,177	
Total	55				

[1] Fourth harvest.

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 87.--Analysis of variance for data shown in Table 50.

		Harvests									
		1		2		3		4		Roots	
Source	df	MS	F	MS	F	MS	F	MS	F	MS	F
Rep	3	0.52	1.44	8.11	2.91	6.65	1.28	5.64	0.49	0.07	0.08
Lime	2	29.83	82.86**	36.59	13.11**	61.82	11.89**	28.04	2.44	14.10	16.79
Micronutrient	3	0.59	1.64	0.89	0.32	0.18	0.03	3.67	0.32	0.03	0.04
L x M	6	0.47	1.31	4.41	1.58	5.42	1.04	10.85	0.94	1.75	2.08
Error	33	0.36		2.79		5.20		11.50		0.84	
Total	47										

**Significant at 0.01 probability level.

Table 88.--A summary of F values from the analysis of variance for data shown in Table 51.

		Mn		Zn		Cu	
		Harvests					
Source	df	1	4	1	4	1	4
Rep	3	46.05**	1.85	3.11**	1.25	0.81	1.46
Lime	2	2,017.80**	190.29**	2.14	46.48**	0.88	0.76
Micronutrient	3	12.50**	1.67	3.85*	3.19*	0.08	2.31
L x M	6	6.15**	0.93	5.47**	2.06	1.69	1.51
Error	33						
Total	47						

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 89.--Analysis of variance for data shown in Tables 52 and 54.

		Mn chelate		Mn chelate + $MnSO_4.H_2O$	
Source	df	MS	F	Mn	F
Rep	2	0.51	0.57	0.31	0.27
Lime	2	31.55	44.44**	36.76	32.24**
Mn	2	2.28	2.56	0.50	0.44
L x Mn	4	3.20	3.60*	1.48	1.30
Error	16	0.89		1.14	
Total	26				

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 90.--Analysis of variance for data shown in Tables 56 and 57.

		Harvests							
		1		2		3		4	
Source	df	MS	F	MS	F	MS	F	MS	F
					Forage yields				
Rep	3	0.16	0.44	1.50	0.78	4.07	1.16	0.57	0.37
Treatment	7	1.34	3.72**	6.92	3.59**	3.03	0.87	2.25	1.44
Error	21	0.36		1.93		3.50		1.56	
Total	31								
					P concentrations				
Rep	3	0.000053	0.30	0.00009	0.56	0.00019	0.68	0.00004	0.21
Treatment	7	0.000539	3.08*	0.00053	0.04	0.00018	0.64	0.00035	1.84
Error	21	0.000175		0.00016		0.00028		0.00019	
Total	31								

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 91.--Analysis of variance for data shown in Table 58.

Source	df	MS	F
Rep	3	2.33	1.17
Treatment	7	21.00	10.50**
Error	21	2.00	
Total	31		

**Significant at 0.01 probability level.

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BIOGRAPHICAL SKETCH

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This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Agriculture and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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